**INDAL**

# FOR ONCE, WE'RE WELL BELOW THE MARK

WHEN OUR SMELTERS AT ALUPURAM AND HIRAKUD WERE RECENTLY CHECKED FOR FLUORIDE EMISSION, THEY WERE HAPPILY WELL BELOW THE MAXIMUM PERMISSIBLE LIMIT. JUST ONE OF THE MANY INSTANCES BY WHICH WE AT INDAL HAVE SHOWN OUR CONCERN FOR THE ENVIRONMENT. TODAY THIS CONCERN IS MUCH MORE THAN JUST A RS 350-MILLION INVESTMENT IN ENVIRONMENT POLLUTION CONTROL EQUIPMENT FOR OUR VARIOUS PLANTS. IT IS A DEEP-ROOTED COMMITMENT THAT EXTENDS TO ALMOST ALL THAT WE DO — FROM OUR ECO-FRIENDLY MINING TO OUR SOCIAL WELFARE SCHEMES. FROM OUR VOLUNTARY ENVIRONMENT AUDITS TO INNOVATIVE WAYS OF RECYCLING WASTES FOR PRODUCTIVE USE. FROM OUR AFFORESTATION DRIVES TO OUR RECYCLING PROGRAMMES. A COMMITMENT REITERATED BY A WELL-DEFINED ENVIRONMENT MANAGEMENT POLICY. THAT IS DEDICATED TO BALANCING CORPORATE GOALS WITH SOCIAL RESPONSIBILITIES. THE INDAL WAY.

Contract Indal 12943

INDAL

**Indian Aluminium Company, Limited**

*A clean environment with a clear attitude*

# WEALTH from WASTE

# WEALTH from WASTE

*Editors*
Sunil Khanna
Krishna Mohan

*Foreword*
T N Khoshoo

teri

Tata Energy Research Institute

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# Foreword

In an undisturbed ecosystem, waste of one species is food for the others. The net result is that there is no accumulation of waste. On the contrary, one of the inbuilt characteristics of present-day human society is generation of enormous quantities of waste. The 'higher' a human being is in the socio-economic ladder, the higher is he/she in the consumer-chain and greater is the quantity of waste generated. This is on account of his/her being a part of the 'Throwaway Society': rubbish, in a sense, has become an index of high living standards. The underlying rationale of such a society has been that resources of earth are unlimited and infinite. This may have been true when human population was small; but the hard reality today is that human population is out-stripping resource availability.

Present-day resource utilization and waste generation are far beyond the carrying capacity of the biosphere. Today, humankind is trapped in a vicious cycle, both of increasing numbers and increasing wants. The result is increasing wastes and declining resources, making the situation unsustainable.

Single-use of resources is increasingly going to be a thing of the past. The guiding philosophy of the human race has to be: reduce; recover; recycle; reuse; repair; and restore resources. The availability of recycled paper and such other goods is now commonplace even in industrial countries; this is a sign of commitment to resource conservation. It not only saves the use of virgin resources but also energy. Some wastes can also be used for generating other eco-friendly products like compost and energy. What is waste for one industry could, in the course of time, become raw material for another.

Abundant waste available from municipal corporations and agricultural, horticultural, industrial, mining and building activities can materially add to the national wealth. Mercifully, recycling and reuse of paper, plastics, cans, bottles, scrap, and old clothes has always been a part of the small trade in our country. It generates small-time employment for poorer sections of our society, although ultimately big business creeps into making big profits. Thus the poor do the dirty work, the rich reap the harvest of profits.

There is a silver lining: recycling and reuse of wastes is fast becoming one of the flourishing industries because one-time use of material is being increasingly regarded as a symbol of a negligent consumer society.

There is an instructive story about reuse of materials given in Lord Buddha's teachings (*The Teaching of Buddha*, Buddhist Promoting Foundations, Tokyo):

> 'Shyamavati, the queen-consort of King Udayana, offered five hundred garments to Ananda (the favourite disciple of Buddha) who received these with great satisfaction.
>
> The King, hearing of it, suspected Ananda of dishonesty, so he went to Ananda and asked what he was going to do with five hundred garments. Ananda replied: Oh King, many of the brothers in the Order are in rags; I am going to distribute the garments among the brothers.
>
> What will you do with the old garments?

*We will make bed-covers out of them.*
What will you do with the old bed covers?
*We will make pillow cases.*
What will you do with the old pillow cases?
*We will make floor covers of them.*
What will you do with old floor covers?
*We will use them for foot towels.*
What will you do with the old foot towels?
*We will use them for floor mops.*
What will you do with the old floor mops?
*Your Highness, we will tear them into pieces, mix them with mud and use the mud to plaster the house walls.'*

There cannot be a better example of reuse of materials than this—a concept which has been ingrained in our history, culture, religion, and philosophy. Indians, particularly women, no matter whether they are literate or illiterate, rich or poor, from higher or lower social groups, are generally more educated than men as far as environment is concerned. Furthermore, according to Buddha, 'Every article entrusted to us must be used with good care in some useful way, because it is not "ours" but is entrusted to us temporarily.'

Business and trade have to realize that, while there was a time when there was money in exploiting resources (timber, coal, metallic and non-metallic minerals, petroleum, etc.), there is going to be increasingly more money in the conservation and efficient use of resources in future. Environmental protection, therefore, should be an in-built component of business management involving manufacture, handling, transport, use, and safe disposal of various products without any risk to the environment. Eco-labelling of products has to become an integral part of technology and business.

The path to environment-friendly technologies is being vigorously pursued in developing countries. Like all new technologies, these may be costly to begin with, and their transfer to developing countries may also pose problems. Such problems have to be resolved at the international level through eco-diplomacy.

In the development of biological products, microorganisms play many varied and even weird functions. This planet would have been the dirtiest of places without them. They carry out systematic degradation and conversion of wastes by using the large arsenal of enzymes they posses. This group of organisms will in due course be utilized to make useful products even from non-biodegradable wastes.

The present book (*Wealth from Waste*) is, therefore, a most welcome and timely contribution from the Tata Energy Research Institute (TERI). TERI has taken up the challenge of waste utilization using microbes, which is the technology of the future. In any sustainable form of development, such technologies would be the most important, because the age of single-use of materials is on the way out.

TERI deserves hearty congratulations for a job well done.

T N Khoshoo

# Preface

---

Waste has always been associated with human activity, and is a necessary evil in any developmental process. Today, however, the sheer quantity and diversity of wastes generated by industries and municipalities pose serious risks to both human health and the environment. The situation is particularly bad in developing countries such as India. Inefficient technologies, ineffectual policies, and insensitivity on the part of the industrial sector have led to large-scale degradation of the ecosystem by domestic and industrial effluents. It is imperative, therefore, that relevant technologies are evolved to treat and recycle wastes.

This book is an effort to put together the various options available to meet the twin goals of environmental conservation and sustainable development. It comprises a collection of carefully selected articles, from both specialists and entrepreneurs, on what is possible today in the field of waste management. Existing policy instruments and regulatory mechanisms in India are also examined.

The main impetus for this endeavour came from a workshop with the same title held in early 1994, organized by our Institute and sponsored jointly by *British High Commission (British Council Division)* and *Shriram Industrial Enterprises Limited*. This book contains much of what was presented at the workshop, as well as specially commissioned articles by eminent personalities in the field. Our sincere thanks are due to each one of the authors. Again, this book would not have attained its present form without the active involvement of the Publications Unit, TERI. Our thanks are due to Ms Beena Menon, Mr R K Joshi, Mr Gopal Krishnan, Mr R P Subramanian, Ms Neena Bakshi, and Mr T Radhakrishnan in this regard. Special mention must be made of Mr K P Eashwar and Ms Poonam Deveshwar whose untiring efforts have enabled us to bring out the book.

Editors

## 1

# Environmental legislation and enforcement mechanism

**Dilip Biswas**
*Central Pollution Control Board, New Delhi*

## INTRODUCTION

The Constitution of India contains a direct commitment to environmental protection. Article 48-A of our Constitution stipulates that *the State shall endeavour to protect and improve the environment and to safeguard the forests and wildlife of the country*. Under Article 51-A(g), citizens are requested to *protect and improve the natural environment, including forests, lakes, rivers and wildlife*. The Directive Principles under Article 49 and 51-A(f) also recognize the importance of protecting the sites of cultural heritage as part of the total environment. Thus, our Constitution provides the necessary bedrock for framing and enforcement of environmental legislations.

Schedule VII of the Constitution classifies the various legislative subjects into three categories, namely, Union list, State list, and Concurrent list. The legislations in the Union list are enacted by Parliament, while in the case of the State list, the state legislatures are empowered to enact the necessary legislation. The third category, the Concurrent list, specifies the subjects that are to be looked after jointly by the central and state governments. Though the subject *environmental pollution control* as such does not figure anywhere in these lists, various individual sectors are specifically provided for in one or the other of these lists. For instance, while *water supplies, irrigation and canal drainage, etc.* are State subjects, *the regulation and development of inter-state rivers and river valleys* are Central subjects. Subjects like *public health and sanitation, agriculture, protection against pests and prevention of plant diseases* find place in the State list. On the other hand, *prevention of the extension from one state to another of infectious or contagious diseases* is included in the Concurrent list. Forests and protection of wild animals and birds are also some of the subjects figuring in the Concurrent list. In the national interest and in certain special circumstances, the Constitution enables the Parliament to legislate with respect to matters in the State list (Article 249 and 252). For instance, Parliament is empowered to legislate on all subjects of International Agreements to which our country is a party (Article 253).

The various Acts relating to pollution control and environmental protection could be broadly classified into two categories, namely, central and state enactments. Some of the important Acts are listed in Annexure (see page 8).

In accordance with constitutional provisions, the Water (Prevention and Control of Pollution) Act, 1974 was promulgated under Article 252 as water is a State subject. On the other hand, the Air (Prevention and Control of Pollution) Act, 1981 was passed under the provisions of Article 253, since air does not figure in the Central or State list.

In spite of all these Acts and implementing authorities, serious lacunae have been found in dealing with aspects relating to hazardous chemicals and siting of industries. However, the catastrophic leakage of methyl isocynate gas from the Union Carbide Factory in Bhopal brought out the need for providing *teeth* to the Acts for deterrent action, where warranted. The necessity to have an umbrella legislation was also felt for taking appropriate measures on various aspects of environmental concern including those that are not covered under the existing laws. Thus, the Environment (Protection) Act, 1986, promulgated under Article 253 of the Constitution, was brought into force with effect from 19 November 1986.

## THE ENVIRONMENT (PROTECTION) ACT, 1986

The Environment (Protection) Act, 1986 enables the Central Government to:

- take all necessary measures for protecting the quality of environment;
- coordinate the action of state governments, officers, and other authorities under this Act or under any other law that is relatable to the objects of this Act;
- plan and execute a nationwide programme for prevention, control, and abatement of environmental pollution;
- lay down standards for discharge of environmental pollutants;
- empower any person to enter, inspect, take samples and test;
- establish or recognize environmental laboratories;
- appoint or recognize government analysts;
- lay down standards for the quality of environment;
- lay down procedures and safeguards for handling hazardous substances;
- restrict areas in which any industries, operations or processes may not be carried out or shall be carried out subject to certain safeguards;
- lay down safeguards for prevention of accidents and take remedial measures in case of such accidents;

- constitute an authority or authorities for exercising its powers;
- issue directions to any person, officer or authority, including the power to direct closure, prohibition or regulation of any industry, operation or process, or stoppage or regulation of supply of electricity, water or any other service;
- require any person, officer, state government or authority to furnish any prescribed information; and
- delegate powers to any officer or state government or authority.

According to Section 19(b) of the Act, any person can complain to the court upon any violation of the provisions of the Act, after issuing a notice of 60 days to the concerned authority. The notice is intended for two purposes. During this period, the authorities who receive the notice may verify whether the complaint is genuine and, if it is so, they may prosecute the offender so that the complainant is not burdened with the cost of litigation. If the complaint is found incorrect, the authorities can inform the complainant. The complainant may still choose to proceed with his complaint at the end of the 60th day irrespective of the findings of the authority. Even if the pollution is stopped within 60 days, pollution against which a complaint is made will still be punishable.

The Act makes it obligatory on the part of the person in charge of a place to inform the concerned authorities regarding any discharge or apprehended discharge of any pollutant exceeding prescribed standards. The authorities, on receipt of such information or otherwise, shall cause remedial measures to be taken to prevent or mitigate the pollution caused by such accidents. The expenses incurred by the authorities in respect to remedial measures are recoverable with interest from the polluter.

The Act prescribes stringent penalties for violation of the provisions of the Act. The jurisdiction of civil courts is barred under the Act.

## ENFORCEMENT MECHANISM

Environmental protection covers a diverse spectrum of areas in the country and is dealt with by a number of existing agencies. For instance, there are a number of legislations which are implemented by various agencies such as Factories Inspectorates, Insecticides Inspectorates, Inspectorate of Explosives, and Pollution Control Boards (PCBs).

Taking into account the expertise available with the existing agencies, the Central Government decided that the Environment (Protection) Act, 1986 be implemented through the existing agencies as far as possible.

Several steps have been taken so far to provide legal and institutional basis for implementation of the Act. These include framing of rules, notification of standards, enlisting environmental laboratories, strengthening of state departments of environment and PCBs, delegation of powers, identification of agencies for carrying out various activities, for hazardous chemicals management, and for setting up of environment protection councils in various states. Some of the important developments that have taken place after the Act came into force are briefly mentioned in the following sections.

## Formulation and notification of standards

The Central Pollution Control Board has prepared effluent standards for industries. These standards have been analysed by expert committees, and the effluent standards for a number of industries have been statutorily notified. These include: (i) caustic soda, man-made fibres; (ii) oil refineries; (iii) sugar, thermal power plants, cotton textiles, composite woollen mills; (iv) cement; (v) electroplating; (vi) dyes and dye intermediates; (vii) stone crushing; (viii) coke ovens; (ix) synthetic rubber; (x) small pulp and paper; (xi) fermentation; (xii) leather tanneries; (xiii) fertilizer; (xiv) aluminium; (xv) calcium carbide; (xvi) carbon black; (xvii) copper; (xviii) lead and zinc smelting; (xix) nitric acid; (xx) sulphuric acid, iron and steel, and rubber. Among others, emission standards have been notified in respect of asbestos, chlor-alkali, thermal power plants, large pulp and paper, integrated iron and steel, and reverberatory furnace.

## Environmental laboratories and government analysis

Information was sought from various laboratories in the country with a view to recognizing them as environmental laboratories. Laboratories adequately equipped, and with qualified manpower, have been recognized as environmental laboratories and technically qualified persons have been appointed as government analysts.

## Delegation of powers

Consistent with the policy of utilization of existing agencies, rules have been notified delegating certain powers to the officers of the following agencies of the central and state governments throughout the country.

- State Governments
- Factories Inspectorates
- Dock Safety Inspectorates
- Indian Bureau of Mines
- Port Authority
- Inspectorate of Plantations

- Marine Department
- Central and State PCBs
- Transport Authorities of the States
- Food (Health) Authorities of the States
- Atomic Energy Regulatory Board
- Drug Controllers and Inspectors
- Chief Controller and other Controllers of Explosives
- Insecticides Inspectorates
- Inspectorate of Boilers
- Directorate General of Shipping
- Officers under the Smoke Nuisance Acts of West Bengal, Maharashtra, and Gujarat
- Collectors of Revenue Districts

## Hazardous substances

The Act entrusts the Central Government with the responsibility of laying down procedures and safeguards for handling of hazardous substances to prevent accidents, which might cause environmental pollution, and for taking remedial measures if accidents occur.

Regarding hazardous chemicals, the existing systems cover only a few aspects of some chemicals under legislations such as Insecticides Act and Explosives Act. After a review of the existing procedures, states have been asked to send proposals for financial support for creating a management structure for prevention and control of chemical accidents.

Various agencies of the central and state governments have been identified to look into the following aspects and take further action.

- Listing of hazardous chemicals and maintenance of a data bank
- Prescribing procedures with reference to manufacture, storage, import, transport, use and disposal of hazardous chemicals, and implementation
- Prescribing procedures for location of chemical industries and implementation
- Guidelines for safety measures and audit of hazardous installations and implementation
- Procedures for preparing on- and off-site emergency, and post-emergency plans and implementation
- Procedures in case of accidents
- Research

A list of hazardous chemicals has been prepared after conducting surveys in various states by technical experts, and consulting similar lists prepared in other countries. The list was circulated to experts, central and state government agencies, and the Chemical Industry Association for their comments. Based on their expert opinion, rules have been prescribed for handling priority chemicals and preparing emergency plans for hazardous installations.

Guidelines for a Crisis Management Plan for chemical accidents have been prepared and circulated to state governments and concerned central departments for follow-up action. An organizational structure has been proposed at central, state, and local or district levels for the management of chemical accidents. The guidelines also provide composition of various committees and mobilization of essential services including communication during the crisis. Concerned central agencies have been asked to designate officers and the states to constitute similar crisis groups at state and district levels.

Rules for the manufacture, use, import, export, and storage of hazardous microorganisms/genetically engineered organisms or cells have been prescribed.

## Show-causes and directions for closure

The central and state governments issue show-cause notices to industrial units if they violate the pollution control norms. After this step, directions for closure are issued or time is given for setting up effluent treatment plants.

## Notification for ecologically important areas

Under the Environment (Protection) Act, 1986, a directive has been issued whereby location of industries (except those which are engaged in the promotion and development of tourism and those which are permitted by the Central Government after examining the environmental impacts) within 1 km along the coastline of Murud Janjira in Maharashtra has been prohibited. This was done to protect the natural ecological features of the area from indiscriminate industrial activities. This area could probably be gainfully used for tourism-related activities.

The Doon Valley—bounded by the Mussoorie ridge line, lower Himalayan ranges, Shivalik ranges, Ganga, and Yamuna—is an ecologically fragile area. This area has been subjected to considerable environmental degradation due to industrialization, mining operations, deforestation, excessive grazing, and unrestricted tourism activities.

Industries have been classified into three categories—green, orange, and red. The green category units are non-polluting industries and the orange category industries are those which can be permitted with adequate pollution control measures. The red category industries are highly polluting and are not permitted in the Doon Valley. A notification has also been issued under the Environment

(Protection) Act, 1986 for regulating the location and types of industries, mining operations, tourism development, grazing, and land-use in the Doon Valley.

## CONCLUSIONS

The Environment (Protection) Act, 1986 has provisions for a fairly comprehensive coverage to deal with various aspects including pollution, environmental degradation, and protection of ecologically important areas. The Act provides for setting up of new institutional mechanisms, where called for. It has empowered the concerned authorities to issue necessary directions including closure of installations/activities causing pollution or environmental degradation. Stringent penalties with imprisonment and fine have also been prescribed in the Act.

However, an Act is as good as it is implemented and there are several obstacles to its effective implementation. Apart from the administrative machinery at various levels, which needs to be geared up, a major hurdle is in terms of legal structures. More often than not, the legal proceedings are inordinately long-drawn and the decisions are delayed in the process. To enable them to function effectively, it is all the more necessary to strengthen/restructure PCBs and similar authorities. The manner in which the legal proceedings could be expedited (and avoided in certain cases) is also to be examined.

While the Environment (Protection) Act, 1986 and other Acts, as amended over the recent past, have been provided with powerful *teeth*, the *claws* for the grip in terms of administrative and organizational structure as required for the purpose are lacking. In order to have an organic linkage among the concerned agencies at the central and state levels, creation of an all-India cadre of Environment Protection Service could be a possible means for building up cohesive enforcement machinery.

ANNEXURE

## ENVIRONMENTAL LAWS IN INDIA

### General enactments

#### *Water pollution*

1. The River Boards Act, 1956
2. The Merchant Shipping (Amendment) Act, 1987
3. The Water (Prevention and Control of Pollution) Act, 1974, amended in 1988
4. The Water (Prevention and Control of Pollution) Cess Act, 1977
5. The North India Canal and Drainage Act, 1873
6. The Indian Fisheries Act, 1897
7. The Damodar Valley-Corporation (Prevention of Pollution of Water) Regulation Act, 1948
8. The Environment (Protection) Act, 1986

#### *Air pollution*

1. The Air (Prevention and Control of Pollution) Act, 1981, amended in 1987
2. The Indian Boilers Act, 1923
3. The Factories Act, 1948, amended in 1987
4. The Industries (Development and Regulation) Act, 1951
5. The Mines and Minerals (Regulation and Development) Act, 1947
6. The Oriental Gas Company Act, 1857
7. The Indian Explosives Act, 1884
8. The Explosive Substances Act, 1908
9. The Motor Vehicles Act, 1938, amended in 1988 and Rules, 1989
10. The Inflammable Substances Act, 1952
11. The Petroleum Act, 1934 and Rules, 1979
12. The Environmental (Protection) Act, 1986

#### *Noise pollution*

1. The Environmental (Protection) Act, 1986

#### *Marine pollution*

1. The Share Nuisance (Bombay and Colaba) Act, 1953
2. The Obstruction in Fairways Act, 1891
3. The Indian Fisheries Act, 1897
4. The Indian Ports Act, 1908
5. The Major Port Trusts Act, 1963

6. The Merchant Shipping (Amendment) Act, 1987
7. The Territorial Waters, Continental Shelf, Exclusive Economic Zone, and other Maritime Zones Act, 1976
8. The Coastguards Act, 1978

### *Hazardous substances*

1. The Poison Act, 1919
2. The Dangerous Drugs Act, 1930
3. The Drugs and Cosmetics Act, 1940
4. The Factories Act, 1948, amended in 1987
5. The Prevention of Food Adulteration Act, 1954
6. The Industries (Development and Regulation) Act, 1951
7. The Insecticides Act, 1968
8. The Environment (Protection) Act, 1986
9. The Consumer (Protection) Act, 1986

### *Radiation*

1. The Atomic Energy Act, 1962
2. Radiation Protection Rules, 1971

### *Pesticides*

1. The Insecticides Act, 1968
2. The Factories Act, 1948
3. The Poison Act, 1919

### *Forest and wildlife conservation*

1. The Indian Arms Act, 1978
2. The Wildlife (Protection) Act, 1972
3. The Indian Forests Act, 1927
4. The Forest (Conservation) Act, 1980, amended in 1988

### *Others*

1. The Urban Land (Ceiling and Regulation) Act, 1976
2. The Prevention of Food Adulteration Act, 1954
3. The Ancient Monuments and Archaeological Sites and Remains Act, 1958
4. The Slum Areas (Improvement and Clearance) Act, 1956

## State enactments

### *Water pollution*

1. The Orissa River Pollution Prevention Act, 1953
2. The Maharashtra Prevention of Water Pollution Act, 1969

### *Smoke control*

1. The Bengal Smoke Nuisance Act, 1905
2. The Gujarat Smoke Nuisance Act, 1963
3. The Bombay Smoke Nuisance Act, 1912

### *Pest control*

1. The Andhra Pradesh Agricultural Pests and Diseases Act, 1919
2. The Assam Agricultural Pests and Diseases Act, 1954
3. The Uttar Pradesh Agricultural Diseases and Pests Act, 1954
4. The Mysore Destructive Insects and Pests Act, 1917
5. The Kerala Agricultural Pests and Diseases Act, 1958

### *Land utilization and land improvement*

1. The Andhra Pradesh Improvement Scheme Act, 1949
2. The Acquisition of Land for Flood Control and Prevention of Erosion Act, 1955
3. The Bihar Waste Lands (Reclamation) Cultivation and Improvement Act, 1946
4. The Delhi Restriction of Use of Land Act, 1964
5. The Madhya Pradesh Nagar tatha Gram Nivesh Adhiniyam, 1973
6. The Madhya Pradesh Gandhi Basti Kshetra (Sudhir tatha Nirmulan) Adhiniyam, 1976
7. The Madhya Pradesh Town (Periphery) Control Act, 1960
8. The Madhya Pradesh Regulation of Uses of Land Act, 1948

### *Forest and wildlife conservation*

1. The Madras Elephants Preservation Acts, 1873 and 1879
2. The Nilgiris Game and Fish Preservation Act, 1879
3. The Indian Arms Act, 1978
4. The Wild Birds and Game Protection Act, 1887
5. Notification in 1902 under the Sea Custom Act, 1878
6. The Wild Birds and Animals Protection Act, 1912
7. The Bengal Rhinoceros Protection Act, 1932
8. The Punjab Wild Birds and Wild Animals Protection Act, 1933
9. The Andhra Pradesh Forests Act, 1967

*Note.* Further information on any of these can be obtained from the Central Pollution Control Board.

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# 2

# Managing the environment—some issues

**Kapil K Narula, Atul Kansal, and Veena Joshi**
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## INTRODUCTION

The goal of sustainable development is implicit in the Eighth Plan document. The document underlines the significance of ensuring coordinated and integrated governmental action for conserving nature and sustainable use of natural resources. Sustainable development, which has become the goal for human welfare after the 1992 United Nations Conference on Environment and Development (UNCED), is, however, rooted in the country-specific programmes of action for channelling investment resources into ecologically compatible projects and programmes. The National Policy on Education (NPE) 1986, as revised in 1992, observes that *there is a paramount need to create a consciousness of the environment and must permeate all ages and all sections of society*. In India, the urban sector contributed 47% of the gross domestic product in 1980/81 and is likely to go up to 60% by the year 2001.

The objective is to integrate environmental considerations into decision-making at all levels. To achieve this, steps have been taken to:

- prevent pollution at source;
- encourage, develop, and apply the best available technical solutions;
- ensure that polluter pays for the pollution and control arrangements;
- focus attention on heavily polluted areas and river stretches; and
- involve the public in decision-making.

Regarding international agreements, India is a signatory to six important conventions that have a direct bearing on the environment protection and conservation. These are: (1) the Convention on International Trade in Endangered Species (CITES); (2) the Convention on Wetlands of International Importance (the Ramsar Convention); (3) the Convention on Climate Change; (4) the Convention for Conservation of Biological Resources; and (5) the Vienna Convention/Montreal

Protocol on substances that deplete the ozone layer. In addition, India is also a party to the *Rio Declaration on Environment and Development* and Agenda 21. The operational programme for sustainable development has also been adopted at the UNCED in Rio de Janeiro in June 1992.

This paper focuses on the ongoing regulatory strategies for capturing environmental sensitivity and sensibility in India and attempts to highlight the various control measures that could be implemented to bring about better enforcement in the present scenario, taking into account the experience of the west. It also lays a suggestive emphasis on both cleaner technologies and waste management, which could reduce pollution to very low levels, thereby controlling pollution from *cradle to grave*.

## PROFILE OF ENVIRONMENTAL CONCERNS IN INDIA

The establishment of a diversified industrial structure depends upon a combination of large- and small-scale industries and the growing urban and rural population, its effect on air, water, and land resources.

The levels of air pollution in many regions have far exceeded permissible limits, resulting in increased health risks and larger environmental threats such as global warming and acid deposition. The pollution load in respect of air is of a relatively high order in metropolitan cities such as Delhi, Bombay, Calcutta, and Madras. Ambient air quality status during 1990 shows a maximum concentration level of 1480 micrograms per cubic metre ($\mu g/m^3$) in Delhi, 601 $\mu g/m^3$ in Calcutta, 306 $\mu g/m^3$ in Madras, and 474 $\mu g/m^3$ in Bombay for residential areas. The Central Pollution Control Board (CPCB) studies indicate that the periods from April to June and mid-October to March are environmentally critical for Delhi from the point of view of air pollution [1].

Rivers and streams in India suffer from very high levels of pollution. Untreated sewage and other non-industrial wastes are the major cause, accounting for four times as much pollution as industrial effluents. According to a study of water pollution in the Ganga basin, under the major Ganga Action Plan of India, it is estimated that three-fourths of the waste water generated are from municipal source, of which 88% is from Class I cities. The pathetic situation is that from Class I cities of the country, only less than five per cent of the total waste water generated is collected and less than one-fourth of this is treated. Such pollution results in high rates of water-borne diseases, which account for two-thirds of all illnesses in India. CPCB studies indicate that, on an average, 90% of the water supplied is *polluted* and only 1.6% of it gets treated [2].

Land is a limited resource, especially when India has 15% of the world's population and only 2.4% of the world area. The combustion of non-renewable fuels as a source of cooking energy in the country has resulted in excessive exposure of women and children to indoor air pollution while depriving the soil of important nutrients, which would otherwise be recycled through biomass decay. The recorded forest cover in the country is 75.01 million ha, which works out to 19.5% of the total geographical area against the broad national goal of 33% for the plain areas and 66% for hilly regions.

Despite many regulatory measures, India has not been able to contain the degradation of our natural resources. The promotion of environment-friendly solutions has not been picking up. So far decentralized small-scale hydropower schemes are not implemented on a significant scale, although they possess the potential of providing economical, efficient, and environmentally benign sources of energy. Biomethanation is an energy-efficient and environmentally compatible process, which could provide five times the energy yielded by combustion of non-renewable fuel sources. But, as yet, it has been exploited only for substrates such as cow-dung. The potential for biogas generation from other substrates largely remains untapped. However, the distillery industry has now realized the use of methane as a substitute to the boiler fuel in use, and it has been estimated that nearly 21 000 $m^3$ of biogas from the biomethanation of waste water can replace approximately 25 metric tonnes of coal per day. Table 1 shows the industry-wise potential of biogas generation in different countries.

The Central Government, in consultation with the states, has evolved an Action Plan to control pollution for heavily polluting industries and critical areas.

TABLE 1. Industry-wise use of biomethanation technology in different countries

| Waste water | Capacity ($m^3$) | Countries |
|---|---|---|
| Sugar beet | 200-3000 | The Netherlands, Germany, Austria |
| Liquid sugar | 30 | The Netherlands |
| Potato processing | 240-1500 | The Netherlands, USA, Switzerland |
| Potato starch | 1700-5500 | The Netherlands, USA |
| Maize starch | 900 | The Netherlands |
| Wheat starch | 500-4200 | The Netherlands, Ireland, Australia |
| Alcohol | 700-2300 | The Netherlands, Germany |
| Yeast | 4400 | USA |
| Brewery | 1400-4600 | USA, The Netherlands |
| Shell fish | 50 | The Netherlands |
| Slaughter house | 600 | The Netherlands |
| Dairy | 450 | Canada |
| Paper (large mills) | 740-4000 | The Netherlands |
| Vegetable canning | 375 | The Netherlands |
| White spirit | 3000 | Thailand |

*Source.* Tata Energy Research Institute, Darbari Seth Block, Habitat Place, Lodhi Road, New Delhi.

Nineteen such problem areas have been identified and surveyed; time-targeted action plans are being framed out in consultation with the respective state pollution control boards (SPCBs). Problem areas that have been identified are listed below.

1. Vishakhapatnam, Andhra Pradesh
2. Digboi, Assam
3. Dhanbad, Bihar
4. Vapi, Gujarat
5. Parwanoo, Himachal Pradesh
6. Kala Amb, Himachal Pradesh
7. Mangalore, Karnataka
8. Greater Cochin, Udyogmandal, Kerala
9. Korba, Madhya Pradesh
10. Chembur, Maharashtra
11. Najafgarh Drain Basin, New Delhi
12. Talcher, Orissa
13. Gobindgarh, Punjab
14. Pali, Rajasthan
15. Manali, Tamil Nadu
16. North Arcot, Tamil Nadu
17. Singrauli, Uttar Pradesh
18. Durgapur, West Bengal
19. Howrah, West Bengal

## MONITORING THE ENVIRONMENT

### Air quality monitoring

The National Ambient Air Quality Monitoring (NAAQM) programme was started in 1984 with 28 stations spread over seven cities. However, now there are about 290 stations under its wing, covering 99 cities. The significant observations made by NAAQM, based on 1990 data, are given below.

- For sulphur dioxide, at 11 NAAQM locations in Ahmedabad, Bombay, Madras, Gajraula, and Howrah, the violations over the 24-hourly average standards were in the range of 5%. At some locations in Madras, Calcutta, and Howrah, it ranges from 5 to 10%. Naskarpara Pump House in Howrah is the only location where $SO_2$ (19%) violated the 24-hourly average standard by more than 10%.

- At three locations, the percentage of violation of solid particulate matter (SPM) over the 24-hourly average standard was more than 80%. These locations are Raipur Road (100%), Clock Tower in Dehradun (90%), and ESI Hospital in Agra (80%).

## Water quality monitoring

Inland Water Quality Monitoring (WQM) is currently being done under three major programmes, namely:

- Global Environmental Monitoring System (GEMS);
- Monitoring of Indian National Aquatic Resources (MINARS); and
- Ganga Action Plan (GAP).

As on 31 March 1992, there were 480 WQM stations of which 51 are under GEMS, 402 under MINARS, and 27 under GAP. Out of the 480 stations distributed all over the country, there are 422 stations on rivers, 26 groundwater stations, and 32 on lakes and creeks. Detailed analyses of the data collected from these.stations reveal that the critical parameters for water pollution are the total coliforms (a biological indicator of pollution) and biochemical oxygen demand. The critical river stretches, which had been identified, are the polluted areas of Sabarmati, Subernarekha, Godavari, Krishna, Indus (tributaries), Sutlej, Ganga (tributaries), Yamuna, Hindon, Chambal, Damodar, Gomati, and Kali. As far as the coastal water quality monitoring is concerned, a network of 173 stations was established during the Seventh Five Year Plan over the entire coastline of the country, at varying distances from the coast, to assess the quality of the coastal and estuarine waters. This programme was jointly taken up by the Department of Ocean Development (DOD) and Ministry of Environment and Forests (MoEF).

## MANAGING THE ENVIRONMENT

The Ministry of Environment and Forests, under the Environment Protection Act (EPA), has framed the minimal national standards (MINAS) to be followed by all industries in the country. These standards refer to the maximum limit of concentration of pollutants in the effluent and emission discharges. These standards can only be made more stringent by the SPCBs. Industry-specific standards for water-use and waste water generation (quantum limits) have been finalized in respect of the following industries, which have subsequently been notified under EPA rules:

- integrated iron and steel;
- sugar;
- fertilizer—nitrogenous and phosphatic (SSP and TSP) excluding manufacture of any acid, and complex fertilizer;
- small pulp and paper (agro-residue and waste paper based);
- large pulp and paper—paper and rayon grade pulp;
- fermentation—maltry, brewery, and distillery;
- caustic soda—mercury cell and membrane cell processes;
- textiles—man-made fibre, nylon and polyester, and viscose rayon;
- tannery;
- natural rubber; and
- starch, glucose, and related products.

The present standards are based on the concentration of pollutants in the effluent and emissions. However, mass-based standards have recently been laid to set specific limits to encourage the minimization of waste, promote recycling, and reuse of materials, besides conservation of natural resources, particularly water. Since the standards will be source-related, they will require for the most polluting industrial processes, application of the best available technological solutions, and also be an instrument for technological upgradation.

National and Zonal Task Forces have been constituted for the implementation of standards in industries like fertilizer, iron and steel, thermal power plants, cement, pulp and paper, and oil refineries. The main functions of the task forces are:

1. to create a forum for industries and SPCBs to interact with a view to hastening the process of compliance of standards;
2. to disseminate to the industries, the latest technologies available for control of pollution in specific industries; and
3. to prepare status of compliance at national level for respective industrial categories.

These task forces interact with the concerned industry representatives and SPCBs, and also take up inspection of pollution control systems installed at sources and monitor the progress of implementation of standards.

The CPCB has selected 18 categories of major polluting industries for priority action. The Ministry has initiated a 15-point Action Plan to control pollution and has directed SPCBs to ensure the compliance of standards in these industries. The pollution control status of 18 categories of industries in 23 states/union territories, including all major industrial estates, has been collected, collated, and compiled. Defaulting units have been identified and action is being taken against them.

**TABLE 2.** Implementation of environmental standards in the industry

| Status | Cement | Thermal power | Pulp and paper | Fertilizer | Oil refineries | Sugar | Distillery |
|---|---|---|---|---|---|---|---|
| No. of units complying with emission standards | 62 | 23 | — | 44 | 6 | — | — |
| No. of units complying with effluent standards | — | — | 118 | 62 | 6 | 180 | 74 |
| No. of units committed to a time-bound programme/ partial treatment | 21 | 42 | 99 | — | — | 95 | 70 |
| No. of defaulting units | 5 | — | 100 | 14 | 6 | 88 | 63 |
| No. of units closed | 6 | 3 | 3 | — | 3 | — | — |

*Source.* Tata Energy Research Institute, Darbari Seth Block, Habitat Place, Lodhi Road, New Delhi.

The heavily polluting industries that have been identified in the Action Plan are as follows.

- For air pollution control—cement, thermal power plants, iron and steel, fertilizer, zinc smelter, copper smelter, aluminium smelter, and oil refinery; and
- For water pollution control—distillery (i.e., fermentation), fertilizer, pulp and paper, basic drugs, dyes and dye intermediates, pesticide manufacturing, oil refinery, petro-chemicals, tanneries, sugar, and pharmaceuticals.

The status of implementation of standards in some major industries is given in Table 2.

## Environmental impact assessment studies of development projects

The major purpose of the National Environmental Policy Act of 1969 is to ensure that the environmental quality is fully considered in the decision-making process.

The vehicle used to accomplish this is the Environmental Impact Statement. It is an objective analysis conducted to identify and measure the likely economic, social, aesthetic, and environmental effects of the proposed action (activity or project) and the various reasonable alternatives. In order to ensure the integration of the environmental considerations with the development projects right at the planning stage, procedures have been instituted for environmental (including forestry) clearance of projects before approval for investment. The identification of impacts requires one to first describe and understand the conditions of the environment prior to the activity. There may be significant differences in impacts for a given activity in different areas.

The measurement of impacts is the next logical step in the impact assessment process. This is done by defining the impacts such as on air quality, noise quality, income, economy, energy, land, historical preservation, water, transportation, and rare or endangered species.

The final step involves the aggregation of project impacts into an overall assessment of the project's effects. At present, the following categories of projects are assessed by the MoEF.

- Thermal power projects
- Atomic power projects
- Mining projects of public sector undertakings
- Industrial projects (following categories):
    - (i) requiring the clearance of the Expenditure Finance Committee or the Public Investment Board;
    - (ii) requiring international funding;
    - (iii) referred specifically to MoEF by state governments or the respective administrative ministries; or
    - (iv) taken up for scrutiny by the MoEF due to public complaints.

## Environmental audits

Environmental auditing (EA), as a policy instrument for abatement of industrial pollution, was introduced in India by the Government of India in 1992. This policy envisages annual environmental performance reports that will be submitted by the industry to pollution control boards, and aims to determine the concerns and responses of industry with respect to environmental issues. It also aims to identify the information and technological gaps, incentives, and programmes that are important for the integration of environmental concerns into decision-making at all levels.

The industrial units are interested in industrial output and adept at making profits, while the regulatory bodies are interested in environmental protection. Their interests seemingly pull in opposite directions. The role of the environmental auditor strikes a balance between them. The auditor represents the common will of the industrial unit and the regulatory body, and assists the industrial unit to attain compliance with prescribed standards and to improve productivity. The auditor also assures optimum protection to the environment. The ideal way to look at environmental audit is to regard it as a practical and realistic management tool, which tends to eliminate anything that is not sustainable. From conservation of resources to protection of the receiving bodies, the auditor investigates all possibilities of harm or risk to all components of the environment.

The EA can be divided into three phases, namely the pre-audit, the on-site, and the post-audit. The pre-audit phase includes nomination of a team, setting out tasks and priorities, and preparation of background report. The on-site phase includes interaction with the local staff through both informal and structured meetings, field inspection, sampling and tests, review of records, tentative findings, and recommendations for actions to be taken. Lastly, the post-audit phase includes the finalization of the report, and proposing an action plan. The action plan may be cast to be implemented in phases and to show the short-term measures separately from the long-term measures. In addition, the environmental audit incorporates an assessment of risks, an investigation into field conditions, and a study for waste utilization [3].

### *Benefits*

- Authenticates the extent of compliance with the standards and regulations.
- Identifies the environmental impacts and risks.
- Induces the confidence of right action among personnel.
- Results in emergence of environment management plan on findings of EA.
- Expedites pollution control budgeting programme.
- Results in conservation of material and energy.
- Opens the market to the environment perspective panoramic public.
- Amplifies industrial image and gains, in competition by promoting schemes and strategies like eco-labelling [3].

It is very important that the practice of EA is not deflected towards routine certification for satisfying procedural requirements of a regulatory body, but be applied to the smallest endeavour that involves any natural resource.

## Waste management

Of late, special focus is being put by the Government of India on minimization of wastes and on measures to dispose them of in an effective manner. On the one hand, there is an increasing demand for raw materials for industrial production and on the other, the dwindling non-renewable resources. Efforts are, therefore, being made for the control of pollution arising out of the disposal of wastes, by conversion of unwarranted wastes into raw materials for various industrial users [4].

The National Waste Management Council, set up in January 1990, focused its attention on the disposal and utilization of urban municipal wastes, industrial wastes, and rural wastes. The subgroup of Industrial Waste Management identified that thermal power plants generated maximum industrial solid wastes per year (30 million tonnes of ash); integrated iron and steel mills producing blast furnace slag and steel milling slag (35 million tonnes); non-ferrous industries like aluminium, zinc, and copper producing red mud (3 million tonnes); sugar industries generating pressmud (3 million tonnes); fertilizers and allied industries producing gypsum (4.5 million tonnes) [5]. The subgroup has also identified areas of application of some important industrial wastes (Table 3).

## Use of environmentally sound technologies

### *Cleaner production*

Cleaner production has been defined by the United Nations Environment Programme as the conceptual and procedural approach to production. It demands that all phases of the life cycle of a product should be addressed with the objective of prevention or minimization of short- and long-term risks to human beings and to the environment. The goal of cleaner production is essentially that of the sustainable development, which involves production processes; product cycles and consumption patterns which allow for human development; and the provision of basic needs without degrading or disrupting the ecosystems in which the human development production philosophy is that the measure should be preventive and integrative [6].

Cleaner technology is the practical application of knowledge, methods, and means in order to provide the most rational use of natural resources and energy, and to protect the environment within the means of man. Clean technology is based on improved manufacturing methods that require less raw materials and energy to obtain equitable levels of output of identical or better quality. It also utilizes wastes and recyclable materials to a greater extent, if not entirely. This technology is dependent upon innovation and a high level of co-operation between different industries, particularly when exchange of certain wastes is involved. There are three broad elements of cleaner technologies. They are:

1. resource conservation technologies aiming at waste minimization at source through production change (substitution/conservation/composition), production process changes involving raw material changes, technology changes, and better house keeping;

**TABLE 3.** Industrial waste management

| Waste | Areas of application |
|---|---|
| Flyash | Manufacture of portland pozzolana cement; manufacture of pozzolana metallurgical cement, slag-flyash cement, and low heat cement; Raw material in OPC manufacture; manufacture of oilwell cement; making sintered flyash lightweight aggregates; cement/silicate bonded flyash/clay binding bricks and insulating bricks; cellular concrete bricks and blocks, lime and cement flyash concrete; precast flyash concrete building units; structural fill for roads, construction on sites, land reclamation, etc.; as filler in mines, in bituminous concrete; as plasticizer; as water reducer in concrete and sulphate resisting concrete; amendment and stabilization of soil |
| Blast furnace slag | Manufacture of slag cement, super sulphated cement, metallurgical cement; non-portland cement; making expensive cement, oilwell, coloured cement, and high early-strength cement; in refractory and in ceramic as sital; as a structural fill (air-cooled slag); as aggregates in concrete |
| Ferro-alloy and other metallurgical slag | As structural fill; in making pozzolana metallurgical cement |
| By-product gypsum | In making gypsum plaster, plaster, plaster boards, and slotted tiles; as set controller in the manufacture of portland cement; in the manufacture of expensive ornon-shrinking cement, super sulphated and anhydride cement; as a hydraulic binder; as mineralizer; simultaneous manufacture of cement and sulphuric acid |
| Lime sludge (phospho-chalk, paper, and sugar sludges) | As a sweetener for lime in cement manufacture; manufacture of lime pozzolana bricks/binders; for recycling in parent industry; manufacture of building lime; manufacture of masonry cement; as a raw material for mini cement plants |
| Chromium sludge | As a raw material component in cement manufacture; manufacture of coloured cement as a chromium bearing material |
| Red mud | As a corrective material; as a binder; making construction blocks; as a cellular concrete additive; coloured composition for concrete; making heavy clay products and red mud bricks; in the formation of aggregate; in making floor and all tiles |
| Pulp and Paper | Lignin |

*Source.* Tyagi P C. 1991. Environmental audit for sustainable development: exchanges of waste. *Encare* **1**: 1.

2. end-of-pipe treatment technologies designed to recover raw materials, energy, water, and by-products; and
3. waste utilization technologies for reclamation and utilization of wastes as secondary raw materials.

The concept of cleaner technologies is being advocated in different parts of the world under various names such as low and non-waste technologies, environmentally sound technologies, waste recycling, residue utilization, and resource recovery technologies [6].

## BENEFITS FROM POLLUTION CONTROL

The existence value of a natural resource is defined as the users' willingness to pay for the knowledge that it is preserved. Given the public goods nature of these resources, there may be one or two polluters, but the receivers of damages from the polluted environment or beneficiaries of preserved environment can be many [7].

Environmental resources can provide multiple benefits. For example, water resources provide irrigation, power, fisheries, drinking water, navigation, and recreation. However, there can be a trade-off between some of these benefits. The use of water for one purpose may permanently pre-empt the possibility of using it for other purposes. In other words, there can be irreversibilities in the use of environmental resources. Unabated pollution for a certain period of time may make the resources permanently useless and pollutants can accumulate over time in a lake, and if, within a certain period, attempts for pollution abatement are not made, the lake can be permanently destroyed.

The problem of choice among alternative uses of environmental resources can be better explained by considering the choice between developmental and preservation uses of these resources. There may be an asymmetry between developmental and preservation benefits. The benefits from development are likely to be decreasing whereas preservation benefits are likely to be increasing over time. Growing population, rising educational levels and increasing per capita income, with people having more income to enjoy recreation, may contribute to increasing preservation benefits over time.

## ENFORCEMENT MECHANISMS

Environmental effects like pollution are called externalities, and result in divergence between the private and the social costs. Private agents treat the largely available natural resources like air, rivers, and oceans as if they were free goods. Over-exploitation of resources also occurs in the case of local and global commons due to enforcement problems as well as ill-defined property rights. Externality is an important form of *market failure*. One possible policy option for correcting market failure arising from an externality is to impose a system of administrative rules and regulations in the form of physical restrictions on emissions and effluents, or constraints on the source of pollution as on location of the plant, process of production, etc. These are commonly called *Command and Control* (CAC) policies. Alternatively, a policy maker can influence the producers' behaviour by changing the prices they face for the pollutants by the use of instruments such as taxes, subsidies, tradable permits and incentive schemes, called *market based instruments* (MBIs). Given the goal of sustainable development, the choice of a mix of policy instruments depends on economic efficiency or cost-effectiveness, financial complications, administrative feasibility, etc. CAC by a strong regulatory agency may be quite cost-effective. But generally, and especially in situations where there are many heterogeneous polluters, a large informal sector, and a weak public administration, command and policies will not work so well.

In contrast, MBIs generally allow each polluting source to decide whether to pay the tax or to undertake additional abatement, with the result that low-cost abatement is selected since each source will abate only if marginal costs of abatement do not exceed the tax rate.

## Pollution tax

The normative theory of externalities, which lays the foundation for the use of MBIs in pollution control, goes back to the pioneering work of Pigou [8]. Pigou recommended taxes on activities generating negative externalities, and subsidies on activities generating positive externalities as a means of internalizing externalities and bringing the choice of the firm in line with what it would have been had it faced the true social cost (benefit) of production.

The appropriate base for the tax should be the damage caused or a close proxy for the damage, such as the volume of emissions [9]. The general rule is to set taxes at a rate equivalent to marginal cost of production plus the incremental value of the externality. An analysis of the working of effluent charges in Organization for Economic Co-operation and Development (OECD) countries shows that only the German effluent charge system in the field of water pollution has a built-in incentive system. It is based on a charges–standards approach. An attractive feature of the scheme is that charge reductions are related to the degree of compliance with standards. The charge rate per unit of discharge was ECU 5.75 in 1981 and raised to ECU 19.20 in 1986. Revenues from charges were used for covering water pollution policy administrative costs. and financial assistance to public and private pollution abatement plants. This scheme was announced in 1976, but implemented only in 1981, giving sufficient time to polluters to take abatement measures [1].

France is one of the few countries where charges on air pollution emissions prevail. Liable actors were industrial firms which had either power generation capacity of 50 MW or more, or discharged over 2500 tonnes of sulphur oxides or nitrogen oxides per annum. The charge was calculated for actual sulphur oxide emissions at the rate of ECU 19 per tonne. Attractive features of this system are its simplicity and restriction of its scope to only large polluters. As a result, the management costs accounted only for three per cent of the total revenues.

## Pollution control regimes—enforcement mechanisms for and in India

The existing regime (CAC type) makes use of the CPCB, an apex board under MoEF, Government of India, which coordinates and guides all SPCBs. The standards and regulations regarding pollution are framed by the CPCB and the MoEF. The primary functions of the boards are:

- enforcement of environment protection laws;
- issue no objection certificates (NOCs) to new industry for locational clearance;
- issue consent order to industries allowing them to discharge pollutants on land, water bodies, and in atmosphere;
- set up standards for permissible quality of treated effluent before final disposal;
- monitor the quality of wastes as per consent orders;
- collect fees, cess;
- publish technical and statistical data related to pollution; and
- disseminate information on pollution through seminars, workshops, exhibitions, etc.

Besides pollution control boards, almost all the states have a Department of Environment and Forests.

## Environmental legislation

In accordance with the constitutional provisions, and as water is a State subject, the Water (Prevention and Control of Pollution) Act, 1974 was promulgated under Article 252. On the other hand, the Air (Prevention and Control of Pollution) Act, 1981 was passed under the provisions of the Article 253, since air does not figure in the Central or State list. In the wake of Bhopal disaster and in recognition of the need for a comprehensive legislation, the Environment (Protection) Act (EPA) was brought into force with effect from 19 November 1986. A number of other legislations have been notified concerning environment. Some of these are listed below.

- The Water (Prevention and Control of Pollution) Act, 1974, amended in 1988.
- The Water (Prevention and Control of Pollution) Cess Act, 1977, amended in 1991.
- The Forest (Conservation) Act, 1980, amended in 1988.
- The Wildlife (Protection) Act, 1972, amended in 1983 and 1991.
- The Air (Prevention and Control of Pollution) Act, 1981, amended in 1988.
- The Environment (Protection) Act, 1986.
- The Motor Vehicle Act, 1983, amended in 1988.
- The Public Liability Insurance Act, 1991.
- A Notification regarding Coastal Regulation Zone, 1991.

The CPCB has laid down ambient standards for both water and air as it is required to do under these Acts. However, the enforcement aspect of these Acts is confined almost entirely to individual polluters and the source specific standards that apply to them. As a consequence, there is little that can be done under these Acts to improve or even preserve ambient air and water quality beyond enforcing the standards which apply to individual polluters. However, Government can always undertake cleaning operation on its own, as in the Ganga Action Plan.

Among the different features of the Water Act, the following are worth noting for present purposes.

- The State Board can demand information from any person in order to ensure compliance with the Act. This information could include the discharge of trade effluents into a stream, and details regarding the installation and operation of pollution control equipment. Failure to comply with directions in this regard is punishable by imprisonment up to three months and/or a fine of up to Rs 10 000. An additional daily fine of Rs 5000 can be imposed for continued non-compliance [Sections 20(2), (3), and Section 41].
- The Board can close down certain activities if it is apprehended that pollution may occur or if it has occurred. It can also move the courts for discontinuation of power and water supply. Non-compliance with a board's directions in these cases is punishable by imprisonment from one-and-a-half years to six years plus fine. If non-compliance continues, a daily fine up to Rs 5000 can be imposed. If non-compliance continues for more than a year after the first conviction, the prison terms could be increased to two to seven years [Sections 24, 32, 33(2), 33A, 41(2), (3)].

- The 1988 amendment to the Act requires that there should be no new discharge of trade effluent or sewage without permission of state boards. The penalty for non-compliance could again range from one-and-a-half years to six years imprisonment plus a fine. Continued non-compliance could raise the sentence to two to seven years plus a fine (Sections 24, 25, 26, 43, 44, and 45).
- Some other acts of commission or omission such as tampering with or damaging devices put up by the boards, obstructing persons acting under the Act, and failure to report the occurrence of an accident leading to water pollution, are punishable by imprisonment up to three months and a fine of up to Rs 10 000. The same would apply to any contravention of the Act for which a penalty has not been specified (Sections 45A, 48).

The central and state pollution control boards, established under the Water Act, were empowered by the Air Act to prevent, control, and abate air pollution also. The main provisions of the Air Act, 1981, such as powers of the boards and penalties, are also similar to those of the Water Act. The following features are worth noting.

- The Central Board is to advise the Central Government on matters of air pollution, coordinate activities of the state boards, specify desirable air quality standards, train persons engaged in controlling air pollution, disseminate information and data relating to the Air Act, etc. The state boards have a similar role within their respective states. The boards are also empowered to establish laboratories and appoint government analysts for analysing samples of air or emissions for purposes of implementing the Act (Sections 16, 17, 28, 29).
- In discharging its duties under the Act, the Board may issue directions including closure, prohibition or regulation of any industry, operation or process; stoppage or control of water or power supply and other services (Section 31A).
- Failure to comply with the Act can invite punishment by prison terms ranging from one-and-a-half years to six years along with a fine. Continuing non-compliance can lead to a daily fine of Rs 5000 and beyond one year the imprisonment terms can be raised to two to seven years (Sections 21, 22, 31A, 37).
- Certain acts of commission or omission such as damage to Board property, provision of false information, and failure to inform the Board regarding actual or likely occurrence of emissions in excess of standards are all punishable by imprisonment up to three months and/or a fine of Rs 10 000 (Sections 38, 39).

The nature of penalties allowed under the EPA is similar to those authorized under the Water and Air Acts discussed above.

According to CPCB, in 1992, no less than 5535 pollution offenders were charge-sheeted across India. Between 1987 and 1992, the central and state pollution control boards won 4881 cases, against 23 890 cases filed in that period [10].

## Fiscal incentives

The available fiscal incentives for pollution control are:

- 100% rate of depreciation on pollution control equipment;
- only 35% rate of the basic customs duty to be payable for pollution control equipment;
- complete elimination of countervailing duty for pollution control equipment;
- excise rebate of over five per cent for specified pollution control equipment;
- 100% deduction of the contributions made by the tax payers to any institution for a programme of conservation of natural resources in computing taxable income; and
- exemption of capital gains arising from the transfer of building, land, machinery, etc. for establishing business in a new place and thereby reducing industrial congestion.

In spite of all these incentives and enforcements, however, our air and water remain filthy. Is this because Indian industrialists do not care about the fines and imprisonment as laid down in the Acts or are they least bothered about the present fiscal incentives schemes [10] ? These questions have no answers as of today.

### *Proposed policies for inducing more efficient enforcement*

*Abatement charges with government clean-up.* The first possible option is an abatement charge on effluents or emissions for firms, which do not achieve source-specific standards and the government taking up the responsibility for pollution abatement. Firms with clean technologies and with effluent treatment plants, carrying out abatement up to MINAS level, are not liable to pay any charge and the charge per unit of pollutant should be set at a level which would encourage most firms with treatment plants to abate up to MINAS level rather than pay charges to the government. Therefore, the government has the responsibility of collecting the charges from these firms and undertaking the treatment operation through a public agency.

*Abatement charges with third party clean-up (NGOs).* The first option places a major abatement responsibility on the government, while it is a well-known fact that the management structure of public sector or government agencies in India is in itself quite cost-ineffective. As a result of this, the publicly-operated effluent treatment plants (ETPs) prove operationally expensive and may take a long time to establish [1].

A more cost-effective option could be a combination of charges with third party clean-up. Government would still work, but indirectly, by contracting private parties and putting up the task of setting up and operating ETPs on to them. Government can help private parties by providing land for ETPs and offering fiscal incentives on purchases of machinery and equipment for ETPs. Now, the enforcing agency would be responsible for ensuring compliance from the polluting firms undertaking their own abatement and the party undertaking abatement for the non-complying firms.

*A tax subsidy scheme.* Under this scheme, a Pigouvian tax per unit of pollution, based on the marginal abatement cost at the MINAS level, will be levied on all firms who fail to achieve the source-specific standards and a per unit subsidy will be offered to firms which carry on abatement beyond the MINAS point. This scheme provides an opportunity for firms with low abatement costs to achieve higher environmental standards.

One attraction of the pollution taxes is a raise in the total national revenue while improving efficiency by persuading firms and households to reduce negative externalities. Taxing commodities with negative externalities will thus reduce not only the efficiency losses arising from the externality itself (say, damage from pollution) but also the efficiency losses related to generating revenue, since the procedure may allow other rates to reduce [1].

If the polluter's emissions are fully determined by the consumption of one good, then taxing the good according to the marginal external costs is equivalent to the emission tax. If the polluting good cannot be sufficiently or fully taxed, a related good should be taxed, if it is a complement to the polluting good, and subsidized, if it is a substitute good [9].

Under this scheme, the polluters must submit returns to a tax authority indicating the tax payable or subsidy receivable on the basis of the effluent volume and pollutant concentration. An independent monitoring authority will undertake the programme to test the authenticity of the statement submitted by the polluter. A fine schedule for submitting false returns can be designed with expected fines greater than the tax; the expected fines can be increased both with the extent of under-reporting and with the number of violations.

*Tradable private permits system.* The three options outlined above deal with source-specific standards. They also entail considerable government intervention, though the extent of intervention is less in the second and third options than in the first option [1].

The tradable permit scheme prevailing in USA requires specification of ambient standards by the government and leaves pollution control operations to the firms. However, the government has to play an important role in the allocation of initial permits, creation of secondary markets for the permits and monitoring compliance by the firms.

In the Indian context, the government should specify ambient standards in a region—for example, water quality in a segment of river and ambient air quality in a town. Once the standards are specified, the volume of pollution permits could be easily determined. Then the government should give the pollution rights to a third party on the basis of bidding, and the bidder who quotes the lowest permit price should be given the pollution rights. The third party, in turn, should sell the pollution rights to the polluters at the quoted price. The level of pollution, the level of abatement, and the income received from the sale of permits could be used by the third party for meeting the initial expenses and for creating a secondary permit market (for permit trading). At this stage, the monitoring and enforcement problems arise. A polluter is in a position to sell permits only when his permit-holding exceeds his actual emissions. Therefore, it has to develop and implement a mechanism for compliance on the part of the polluters.

The advantages of the tradable permit system are given below. (1) The polluters can use their private information about technology, costs, etc. to achieve profit-maximizing levels of abatement. We already know that the aggregate abatement costs are minimized under this system. (2) The government's responsibility is limited to only setting ambient standards and monitoring the behaviour of the third party [1]. Some of the issues for discussion are:

- the extent to which protection of environment is a development concern at the national level;
- adequacy of the current measures for controlling pollution;
- the appropriateness and effectiveness of procedures for monitoring and enforcement; and
- the effectiveness of incentives for waste management.

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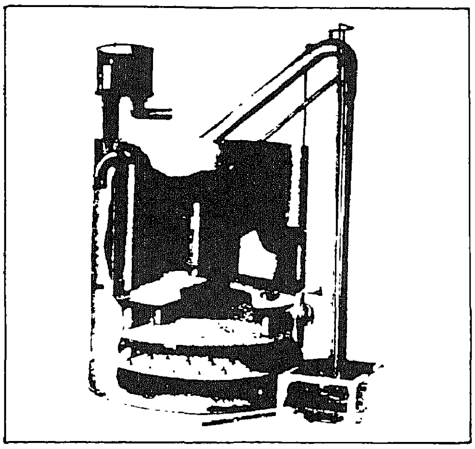

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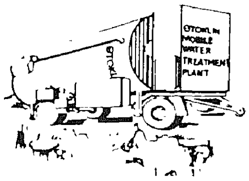

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### 3

# Cogeneration—a technology in waste reduction

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## INTRODUCTION

The industrial sector in India has traditionally been the largest consumer of commercial energy, accounting for about 52% of the total energy consumption. The energy intensity in the Indian industry is much higher than that of the industrially developed countries. Under the New Economic Policy, the industrial sector has undergone a major change due to the liberalization process. It is now faced with a rapidly growing energy requirement to support its economic development. One of the major ways of meeting this requirement is to improve existing energy efficiency and adopt energy-efficient technology like cogeneration, which will cut down production costs and reduce unnecessary consumption of energy. This paper discusses various cogeneration technologies, status of technologies available in the country and abroad, benefits of cogeneration, and some of the barriers related to costs, incentives, pricing, and institutional and legal framework.

Several energy-intensive industries such as sugar, textile, paper, fertilizer, food processing, chemicals, and petrochemicals generate their steam requirements internally and purchase electricity from the grid. Energy-intensive industries have enormous scope for cogeneration. Opting for cogeneration can enable them to produce both steam and electricity internally, thereby reducing the demand for electricity purchased from the utilities. In addition, surplus electricity, if any, can be sold to the utilities. Cogeneration thus provides an alternative to the conventional utility power and reduces the overall emissions from the combustion of fossil fuels, while their efficient utilization is made.

Cogeneration is currently being practised in various industries such as pulp and paper, rayon, sugar, chemicals, and fertilizers. Despite the employment of cogeneration systems in these industries, no efforts have been made to optimize the production of steam and electricity due to various reasons. Also, no efforts are being made to install cogeneration systems, which could generate surplus electricity. Many industries are compelled to continue with non-optimal systems for reasons such as company investment criteria, availability of equipment, incremental costs and reliability, and above all, government regulations.

## CONCEPT OF COGENERATION

Cogeneration is the efficient production of two forms of useful energy from the same fuel resource, using the exhaust energy from one production system as the input for the other. Generally, the primary energy form is thermal (steam) and the secondary form is either electrical or mechanical. The electrical or mechanical energy can be used internally to run company equipment and thus reduce the demand for utility power, and the surplus electricity, if available, can be sold to the utilities. Such a system can reduce energy input to 10–30% of what is required by separate systems to produce the same outputs. Total system efficiency can approach 90%, a significant improvement over the 50–90% efficiency of many industrial boilers and 30–35% efficiency of electrical conversion when separate production is used. As a result, this simultaneous efficient production of two energy forms can significantly reduce total operating costs in many instances, even after paying for the increased capital costs.

## TYPES OF COGENERATION SYSTEMS

### By-product power generation (topping turbines)

In steam turbine systems, by-product power generation implies that power is generated by non-condensing turbine—either by an extraction section or by a non-condensing exhaust section. In both the cases, operation would generally be done in a pressure-governing mode, i.e., the turbine inlet valves and the extraction valves would be regulated in order to maintain constant exhaust and extraction pressure. The amount of power generated would be a function of the process steam demands, and hence, is a by-product of supplying the process heat. In order to meet the total electricity demand, another source of power generation or a utility tie-up would be required.

Most non-condensing steam turbines, which operate on pressure-governing mode, are synchronized with the other source of power. The turbine generator speed is locked into the system frequency, and therefore, speed is not a controlled variable during normal operation. Steam turbine by-product power generation is sometimes called topping turbine power generation.

Any heat engine such as gas turbine or diesel, which supplies useful exhaust heat, is considered to generate by-product power. The power need not be electricity. By-product power can be generated by heat engines, which can drive pumps or compressors directly, even though it would be measured in terms of horsepower instead of kilowatts.

Finally, there can be exceptions to the relationship between by-product power and non-condensing steam turbine power generation. Occasionally, when more electrical power is required than is available from the existing sources in a particular industrial plant, additional steam can be expanded through a non-condensing steam turbine section or recovered in a separate heat exchanger, which condenses the steam (a dump condenser). This steam does not provide any useful heat and is not considered to generate by-product power. This mode of operation is normally limited to transient conditions as there is wastage of energy.

## Condensing power

Automatic-extraction condensing steam turbines have the capability to supply process steam at a controlled pressure and to independently control the amount of electric power generated by the condensing section. Power generated by steam, which is extracted to the process, is by-product power, whereas the power generated by steam expanding to the condenser is not. It is simply referred to as condensing power. But if the condensing steam turbine had no extraction, it would provide only electric power and no useful heat. It would not then qualify as a cogeneration system.

A great deal of energy burned in the boiler for condensing power is rejected to the surroundings through the condenser-circulating water. Hence, the fuel is not used as effectively as in by-product power generation. Some of the reasons for including the condensing section in cogeneration systems are as follows:

- no external power is available from a utility;
- the energy in steam is available at low cost, either from a by-product or waste fuel, or process waste-heat recovery;
- condensing power may be economical to prune peak electric demands and, therefore, to reduce demand charges paid to the utility;
- when the industrial plant has several steam turbine-generators, normal operation would have a minimum amount of condensing power, but the condensing end can be used to full capacity as reserve during shutdown of another generator;
- when the industrial plant has several steam turbine-generators, a condensing section on one unit can simplify dispatching of power among the units; and
- in joint utility/industrial cogeneration schemes, condensing power is another source of generation, which can be dispatched as the economics of the system demands.

There is also an exception to the definition of condensing power. Some heating systems need to heat large quantities of cold water. Here, this water can be preheated by using it as cooling water in the turbine condenser. Therefore, the steam expanded to the condenser also provides useful heat and is considered as by-product power. However, these types of applications are not typical as the quantity of water to be heated, in most cases, is a small fraction of the condenser-cooling water flow.

## Bottoming cycles

A bottoming cycle is generally considered to be one which utilizes waste heat from another source to generate power. Some waste heat sources are:

- gas turbine exhaust gas;
- fired process-heater exhaust gas; and
- process steam which requires cooling.

Exhaust of a gas turbine at 400–600 °C is used to generate turbine inlet steam by a heat recovery steam generator (HRSG). The process furnace stack can also be used to generate steam. In some processes, such as those producing ethylene and ammonia, process steams are heated to 800 °C in a furnace and are then cooled or quenched. This heat can also be used to generate turbine inlet steam.

It should be pointed out that by-product or topping turbine cycles and bottoming cycles are not mutually exclusive, i.e., a non-condensing steam turbine generator can bottom one process-heat source and at the same time top a lower temperature heat requirement. A bottoming cycle can also be a straight condensing steam turbine or an automatic-extraction condensing steam turbine.

The process-heat recovery might also be used from a flue gas of only 300–500 °C. This is too low to generate turbine inlet steam in this case, but adequate for generating 10 bar process steam. When the heat recovery steam generation exceeds the process requirement, the excess steam can be admitted to the turbine generator. Extraction-admission is another feature, which can be specified for cogeneration steam turbines. Power generation cycles, which rely on by-product fuels, are similar to bottoming cycles. Some fuel sources are:

- forest products industries (pulp and paper, plywood, sawmills)—wood waste, sawdust, bark, and black-liquor recovery boilers;
- petroleum and chemical industries—residual hydrocarbons, off-gases;
- basic steel making—coke oven gas, blast furnace gas, balance-of-plant (BOP) off-gases;
- food processing—fibrous waste such as bagasse in sugar refining; and
- refuse disposal plants (trash).

One final comment on the definitions of the various types of cogeneration systems. Most industrial plants, which cogenerate, encompass various system types. For example, bottoming cycles rarely exist in their purest form. They are generally supplemented by some fossil fuel steam generating capacity in order to independently control steam production. Many industrial powerhouses include automatic-extraction condensing steam turbine generators, which are supplied by waste heat or by-product fuel boilers and fossil fuel boilers. Therefore, a single unit often represents a bottoming cycle, by-product power generation or a topping cycle, condensing power cycle, and by-product fuel cycle.

## ENERGY CONSERVATION POTENTIAL

The potential for conserving fuel through cogeneration depends on the user's demand for electricity and heat, and also on the type of cogeneration system to be used. Steam turbine, combustion turbine, and diesel engine systems will each produce a different ratio of electricity to heat output. Fuel conservation will depend on the ability of a cogeneration system to match the user's overall needs for each type of energy output and to cope with fluctuations in the individual demands. Steam is the primary form in which the heat output from a cogeneration system can be utilized. Steam is widely used in industry, and to a somewhat lesser extent in buildings, to transport heat to a point of use. Almost half of all the industrial fuel burned is consumed in generating versatile, easy-to-use steam. A large, well-designed, industrial boiler will convert 85–90% of the combustion heat of the fuel into steam. If this steam is used for heating, and if after such use, the hot condensate water is returned to the boiler, the heat content of the steam can be very effectively used. However, when steam is employed to generate electricity in a modern, high-pressure, high-temperature, single-purpose plant, only 37–40% of the fuel combustion heat is converted to electricity. Most of the remaining heat is carried off by cooling when the exhaust steam passes through condensers at the end of the electricity-generating process. While *rejecting* this large (45–48%) proportion of a fuel's heat energy seems inefficient, the electricity produced is of *high quality*, with the capacity to do more work or generate higher temperature than could be obtained from the rejected low pressure steam.

While cogeneration systems improve the overall efficiency of fuel use, some of the gain is at the expense of electrical power generation. When steam is discharged from a turbine at pressures high enough for heating purposes, electrical power output is reduced proportionately. In a cogeneration system, producing by-product steam at a useful pressure of 50 psi, only about 15% of the input energy will come out as electricity, and almost 70% will remain in the steam.

Cogeneration systems based on diesel engines or combustion turbines can produce higher electricity to steam ratios. However, the ratio for a given system is relatively constant and must match the needs of the installation or it will restrict the energy conservation potential. If the actual demand ratio varies by more than a certain percentage from the design (expected) ratio for the system, it will usually be necessary to simply discard and waste the excess energy output.

Cogeneration systems may encounter highly variable demands for electricity and steam when serving end-uses such as mechanical work, electrical lighting, or heating. An industrial plant may have a peak steam or electricity demand during a particular shift every day. Consequently, demand for electricity may not coincide with a corresponding demand for the cogenerated heat. A useful fuel-conserving cogeneration system must be able to produce electricity and heat (for example, steam) in proportions to match the *load* or array of uses served whenever required. In contrast, a prime attraction of conventional single-purpose systems for process steam, space heating, or electricity generation is that the fuel input and the operating characteristics of the system are controlled by only one output demand.

Different modes of cogeneration will vary in their output ratio of electricity, and high- and low-temperature heat. A basic steam turbine cogeneration system produces only about 15% of electricity with 70% of heat energy in the exhaust steam. A combined cycle cogeneration system using a combustion turbine and an exhaust-heat boiler produces 30% of electricity with 47% of input heat in the exhaust steam. A diesel cogeneration system using an exhaust-heat boiler produces 36% of electricity with 27% of heat in the exhaust steam.

These ratios of electricity-to-steam are based on a steam pressure of three bars, which is somewhat low for average industrial use. For the higher pressures required in many steam systems, the electricity-to-steam ratio will be lower in the case of steam turbine cogeneration; but higher for the combustion turbine or diesel engine modes. However, in any system designed for higher electricity/steam ratios, the fuel consumption per unit of electricity also increases and the energy conservation potential is diminished. The overall efficiency of fuel use in a cogeneration system will, therefore, depend upon the type of system installed as well as the user requirements for electricity and high- or low-pressure steam from the system.

Cogeneration is currently favoured where an industrial plant can satisfy its needs for electricity and steam with a simple basic boiler and steam turbine system. Such plants will use 65–80% of their energy demand as low-pressure (=10 bars) steam, and the remaining 20–35% as electricity. For example, these conditions are found in many paper plants; and the pulp and paper industry is a leader in industrial cogeneration. Approximately 30% of the electricity used in the pulp and paper industry is cogenerated with the steam production in paper mills. Another area where cogeneration has been actively employed, and also integrated into the system, is the fertilizer industry. Almost all the energy requirements of the ammonia and urea plants are met by the steam generated through high pressure waste-heat boilers.

In general, industrial cogeneration systems are designed primarily to satisfy the heating requirements of an installation, and electricity is considered only as a by-product. This electricity might be sold to the local utility grid or used internally. In either case, it replaces conventionally generated electricity in single-purpose power plants. Cogenerated electricity, depending on the system used, is produced with only 40–70% of the fuel normally required in an efficient, single-purpose power plant.

The potential for fuel conservation thus depends upon how much electricity as by-product can be cogenerated, and this will depend upon both steam or hot water heating demand of the user and the mode of cogeneration employed. For a given heating-energy output requirement, steam turbine cogeneration will yield electricity as a by-product with a maximum fuel saving equivalent to 30% of the energy in the steam output. In combustion turbine and diesel engine systems, the overall fuel savings can be equivalent to 70 and 85% of the respective steam-energy output. However, because these two latter modes produce such high electricity-to-steam ratios, the fuel-saving per unit of electricity generated is actually less than that of the steam turbine mode.

The overall potential for fuel conservation using cogeneration depends upon the relationship between the size and characteristics of user demands for low-temperature heat and for electricity and the mode of cogeneration employed. It is unlikely that cogeneration systems, which fulfil the operating and economic requirements of an individual user, will also produce maximum oil and gas savings from a national viewpoint. A user with a high electricity/low steam demand will not be served well by a cogeneration system with a low electricity/steam production ratio, even if that system provides fuel-cheap electricity. Electricity production can *ride* industrial process steam production while attempting to make dual use of fuel. However, the electricity produced, or the steam cogenerated may not be available in the amount required or at the time it is needed. This conflict is but one of the factors hampering realization of the full conservation benefits from cogeneration.

## COGENERATION MARKET

The potential market for cogeneration in industry in future will be influenced by energy prices in India, the economic situation, restructuring tariff regimes and/or the introduction of financial aids. National energy policies could also make the electricity supply industry open for competition.

## Cogeneration in India

There have been very few definitive studies to estimate the potential for cogeneration in India. This section primarily draws upon some of the recent studies and provides the cogeneration potential estimated by them.

The recent initiatives taken by the Government of India in the power sector, and more so in the sugar manufacturing sector, indicate that the state electricity boards (SEBs) are likely to change their tariff structure for the cogenerated power. This shall set a precedent for other industries to exploit these changes and generate surplus power to their maximum potential and export to the grid and/or sell to any third party. The major investment in cogeneration is likely to be realized only by independent producers supported by regional electricity distribution companies and SEBs

### *National Productivity Council study*

National Productivity Council (NPC) carried out a macro study on the feasibility of cogeneration in a wide cross-section of Indian industries in 1979. The study estimated a cogeneration potential of 421 MW in 28 of the 150 units surveyed (Table 1). The study further estimated that over 1500 MW of extra power could be generated with marginal investments, by applying the cogeneration system concept. Reviewing the status of energy systems in these units, the study pointed out the following factors as responsible for sub-optimal systems from the micro and macro perspectives.

- The general tendency for most units is to generate steam at the maximum process pressure. By and large, the demand for low pressure steam is met through pressure reductions.
- Rationalization in choice of process steam pressures has not been resorted to.
- Unutilized boiler capacity for steam generation is high.

**TABLE 1.** Cogeneration potential estimated by the NPC study

| Industry | No. of units surveyed | Total power demand | Cogeneration potential* (MW) |
|---|---|---|---|
| Pulp and paper | 3 | 37.5 | 56 |
| Refineries | 4 | 37.3 | 40 |
| Rayon | 3 | 17.1 | 28 |
| Chemicals | 9 | 33.0 | 47 |
| Fertilizers | 9 | 193.0 | 250 |

*The cogeneration potential has been determined on a site by site basis with regard to suitably tailored power-steam cycles.

- Power is purchased from the grid for driving process prime movers, refrigeration, etc. The reliability of purchased power is questionable and industry has suffered in this respect.
- Maximization of heat recovery from process through waste heat recovery devices has not been made use of.

### *Inter-ministerial Working Group on energy conservation*

The study carried out in 1983 estimated that the economic potential for cogeneration in major industries in India is about 1500 MW.

### *United States Agency for International Development study*

The United States Agency for International Development-sponsored study conducted by Hagler Bailly & Company in 1986–87 focused on the potential for cogeneration in the states of Maharashtra and Gujarat. This study estimated a potential of about 2556 MW for industrial cogeneration in these states during the period 1986–96 (Table 2). The study also revealed that industries such as fertilizer, basic chemicals, refinery, and pharmaceutical have the maximum potential. Topping cycle cogeneration systems account for the maximum potential; one-third lies in existing plants and this could be realized by retrofit or replacement of existing steam-generating equipment. The potential of bottoming cycle cogeneration systems has been estimated at about 50 MW, mainly in refineries and in the fertilizer and petrochemical plants.

Presently, natural gas is available mainly to the fertilizer and petrochemical industries in the country. The study estimated that if natural gas were made

**TABLE 2.** Economic potential for industrial topping cogeneration systems in Gujarat and Maharashtra (1986–96)

| Industry | Potential (MW) |
|---|---|
| Textile | 79 |
| Rayon | 54 |
| Pulp and paper | 57 |
| Refineries | 252 |
| Fertilizer | 712 |
| Basic chemicals | 928 |
| Dyes | 76 |
| Food | 41 |
| Pharmaceuticals | 303 |
| Tire | 13 |
| Soaps | 41 |
| TOTAL | 2556 |

available to all industries, then the potential for cogeneration would be over 3000 MW, over the period 1986–96, in the states of Maharashtra and Gujarat alone.

### *Confederation of Indian Industry study*

The cogeneration potential estimated by the study conducted by Confederation of Indian Industry in industrial topping and bottoming cycles for Maharashtra state is given in Table 3.

**Table 3.** Cogeneration potential for topping and bottoming cycles

| Systems | Potential (MW) |
|---|---|
| Industrial topping systems | 2150 |
| Industrial bottoming systems | 50 |
| Commercial systems—packaged cogeneration unit (studies confined to Bombay city only) | 50 |

### *Tata Energy Research Institute study*

The Tata Energy Research Institute (TERI) has estimated the cogeneration potential of 300 industrial units in the country based on the analysis of data obtained from a questionnaire survey. The estimates are based on the internal heat to power ratios, which would meet the plant's energy requirements, and on the existing production capacities of the various categories of industry. Of the total estimated potential of 7953 MW, the sugar industry accounted for about 65% of the total

**Table 4.** Cogeneration potential estimated by TERI (1993)

| Industry | Potential (MW) |
|---|---|
| Alumina | 59 |
| Caustic soda | 394 |
| Cement | 78 |
| Cotton textile | 506 |
| Iron and steel | 362 |
| Man-made fibre | 523 |
| Paper | 594 |
| Refineries | 232 |
| Sugar | 5131 |
| Sulphuric acid | 74 |
| TOTAL | 7953 |

cogeneration potential. The potential is also significant (500–600 MW) in textile and paper industries (Table 4). If the power maximization options were to be considered, the cogeneration potential would also increase significantly.

## Current status of technologies available in India

A cogeneration system is an integration of various components (energy conversion system, BOP systems, heat source, heat pump, etc.) with the goal of providing electrical and thermal requirements of a specified industrial process. Cogeneration systems can be broadly categorized into two groups—topping cycle and bottoming cycle.

In the topping cycle system, the primary fuel is used to produce electricity and the thermal energy exhausted is used for process heating. In the bottoming cycle system, the primary fuel is used to produce high temperature thermal energy, while the hot exhaust steam is subsequently used to produce electrical energy through waste heat boiler and turbine generator system. The specific components comprising a cogeneration plant will however depend upon the industry, the energy conversion system, and the strategy adopted for sizing the energy conversion system.

A brief status report on the technology and availability of some of the components of a cogeneration system in India is given below.

### *Boilers*

The major boiler manufacturers are Bharat Heavy Electricals Ltd (BHEL), Thermax, Walchandnagar Industries, Texmaco, ISGEC, IBPL, Lipi, ACC–Babcock, and others. Most of the major boiler manufacturers have collaborations with leading boiler manufacturers in the world—for example, Combustion Engineering, Babcock and Wilcox, and John Thompson. Both conventional and fluidized bed combustion (FBC) boilers are manufactured in India.

Conventional boilers are available as packaged or field erected units in a wide range of capacities and with fuel capability ranging from oil, gas, and coal to rice husk and bagasse. Typical examples of large size boilers supplied are 275 tonnes per hour (tph) for coal-fired boilers and 130 tph for oil/gas-fired boilers. Packaged oil/gas-fired boilers of 80 tph are also in use. The large 275 tph boilers (supplied to electric utilities) supply steam at a pressure of 96 kg/cm$^2$ at a temperature of 530 °C. Boilers with steam pressures up to 110 kg/cm$^2$ at 465 °C have also been supplied for industrial applications. Discussions with major users indicate that they have the capacity to manufacture higher pressure boilers. FBC boilers have been manufactured in a wide range of capacities and are being used to fire a variety of fuels such as high sulphur and high ash coal, rice husk, rice straw, and even low grade fuels such as coal washery rejects.

### *Steam turbines*

There are three manufacturers of steam turbines in India. They are APE Belliss, Triveni Engineering Works, and BHEL. APE Belliss and Triveni manufacture turbines in the lower rating range, starting from a few hundred kilowatts to 5–6 MW. BHEL manufactures steam turbines in a wider range of capacities (1–500 MW) for thermal power plants. These turbines are available in different configurations, i.e., simple back pressure, condensing, extraction condensing, and multiple extraction turbines.

In the lower range of capacity (up to 5 MW), steam turbines are being manufactured to operate at pressures of 30–45 kg/cm$^2$. Most of these turbines are supplied to the sugar industry, and these turbines conform to specifications laid down by the National Federation of Cooperative Sugar Factories Limited. Manufacturers of these turbines claim to have the capability to manufacture turbines rated higher than 65 kg/cm$^2$ with maximum extraction at about 22 kg/cm$^2$ for the extraction steam turbines.

BHEL manufactures steam turbines operating at pressures up to 100 kg/cm$^2$ and has the capacity to manufacture machines at higher pressures. Turbines with back pressure of over 22 kg/cm$^2$ have been supplied. BHEL also offers multiple extraction steam turbines with extraction at pressures higher than 22 kg/cm$^2$.

Single-stage back pressure turbines typically operate at an efficiency of 30–40%; for multistage back pressure turbines, the efficiency is in the range of 40–50%. For condensing turbines, typical efficiencies are in the range of 60–70%.

### *Gas turbines*

In India, gas turbines are available from BHEL, Triveni Engineering Works, DLF Energy Systems, and Kirloskar Oil Engines. While BHEL and Triveni supply heavy duty industrial gas turbines (typically in the range of 4.5–38 MW), DLF Energy Systems supply aero-derivative gas turbines (1–5 MW range). BHEL is the only manufacturer of gas turbines in the country and its machines are made in collaboration with General Electric. Triveni and DLF Energy Systems supply Ruston and Allison-GM machines, respectively. Typically, gas turbines operate at an efficiency of 22–26% (under typical Indian operating conditions) in the lower ratings up to 5 MW.

### *Diesel engines*

There are various manufacturers of diesel engines in the country—both high speed and medium speed engines. Low speed and medium speed engines are more suitable for cogeneration application. The major manufacturers in India are Kirloskar Pielstick, Garden Reach, K G Khosla, and Wartsila. The new medium speed engines proposed to be manufactured in the country will be able to use heavy fuel oils up to 50 °C (700 centistoke). These engines, which are in the range of 4–6 MW, would typically operate at an efficiency of 38–43%. In India, there are only a few installations of diesel engine-based cogeneration systems with capacities up to 52 MW.

### *Waste heat boilers*

The main manufacturers of waste heat boilers in the country are BHEL, Thermax, Cethar Vessels, ISGEC John Thompson, Texmaco, Larsen and Toubro, and Kaveri Engineering. Waste heat boilers of ratings up to 62 tph with single pressure and up to 105 tph with dual pressures are being manufactured in the country. Among the smaller units used for operation in a cogeneration system is a 38 tph waste heat boiler. It produces steam at a pressure of 15 $kg/cm^2$ and 256 °C temperature. Installed in a refinery, it uses refinery gas as the heat source. However, most of these waste heat boilers have been supplied to fertilizer and chemical industries and refineries which use process gas, natural gas, and residual oil as the fuel.

The largest fired waste heat boiler manufactured in the country is a dual pressure boiler supplying saturated steam at 39 $kg/cm^2$ and 10 $kg/cm^2$.

## Constraints on promoting cogeneration

While the extent of conservation potential through total energy systems has been well appreciated, as also the numerous advantages one would derive from the concept, there are several barriers to cogeneration, which restrict the adoption of such systems by the industries. The following list of identified cogeneration market barriers is believed to be the most comprehensive available from any reference. The identified barriers were determined as a result of thorough literature search and direct discussions with end-users, equipment manufacturers, and government officials.

1. *Regulatory uncertainty.* The key regulations, which qualify and regulate cogenerators, are relatively new and are still being considered by the utility industry. The SEBs have no regulations concerning cogeneration and only three SEBs have taken steps in this direction, mainly for bagasse-based cogeneration. Changes in government policy concerning other investment incentives, tariff, banking, and wheeling facilities can also greatly affect the market.
2. *Stricter air quality standards.* Pollution regulations, recently introduced by the Ministry of Environment and Forests (MoEF), could substantially add to the initial capital investment required for a cogeneration unit. The increased capital cost and in some cases the reduced system performance, will discourage the use of certain cogeneration technologies.
3. *Changing utility buy-back rates.* Electric utility buy-back rates are negotiated for each cogeneration site and are determined by the utility's avoided costs

at that point in time. As the structure of the utility-industry changes and as more cogeneration capacity is brought on line, these buy-back rates may decrease and, therefore, discourage further cogeneration.

4. *Reluctance to enter the power business.* Most manufacturing concerns have become accustomed to simply purchasing power and generating steam or process heat on-site. The prospect of adding a cogeneration system represents a large capital investment in what is usually an unfamiliar technology.
5. *Electric utility resistance.* Many electric utilities have adequate or excessive capacity at off-peak periods such as during nights, and therefore have little incentive to purchase electrical power from a cogenerator. Other utilities disagree with the distributed on-site power concept, having grown up during a period when large central stations dominated the utility structure.
6. *Lack of cogeneration expertise.* Most industrial concerns do not have in-house personnel capable of evaluating, operating or maintaining cogeneration systems. In general, cogeneration technology expertise has been confined to specific industries, which have traditionally utilized equipment of this type.
7. *Perceived unreliability of gas turbines.* Gas turbines, which are typically perceived as high speed and sensitive equipment, are not generally utilized in many industrial prime mover applications. Most gas turbines are used in power producing applications as peaking generator sets, and do require frequent maintenance due to the severe start-up and shutdown operating cycle.
8. *Limited capital resources.* Many industrial concerns do not have sufficient internal funds, or are unwilling or unable to obtain external funds.
9. *Higher priority of production-oriented projects.* Cogeneration projects are oriented towards energy savings, and therefore take a lower priority than production-oriented projects. Higher returns on investment are typically required with energy saving projects when competing for limited capital budgets with production projects.
10. *Sensitivity to energy prices.* Small variations in the input and output utility costs of a cogeneration unit could easily destroy the economics of the project.
11. *Possible plant closings.* Companies will limit the scope of capital investment targeted at plants that may be severely curtailed or closed as a result of changing business or economic climates. Cogeneration projects typically require years of steady operation to be economically viable and, therefore, are of limited interest in this situation.
12. *Premium fuel availability.* Of late, natural gas and oil are available at reasonable prices to the industrial sector throughout the year. The long-term availability of reasonably priced premium fuel is crucial to the successful implementation of several cogeneration technologies.
13. *Limited floor area.* Most cogeneration systems are retrofitted into existing manufacturing facilities with limited available floor space. Adequate plant

volume for proper operation and maintenance of the cogeneration unit in an area, which is accessible to the plant utility tie-ins, is an important consideration.

14. *High capital cost for cogeneration systems.* The available prime mover technologies limit the potential sizes of cogeneration systems to relatively large and expensive units. The high initial capital cost of cogeneration systems is a barrier for industries with limited financial strength.
15. *Proper size and thermal-to-electric output match.* Accommodating the application's energy steam requirements with that available from various technologies is instrumental to a successful project. Most cogeneration technologies have relatively fixed thermal-to-electric outputs and most applications have daily and/or seasonal variations in utility requirements.
16. *Adequate water supply.* Many cogeneration technologies, which utilize heat recovery boilers, require a steady supply of high quality feedwater.
17. *New production technologies that reduce energy use.* New technologies, which could drastically reduce the utility requirements of current industrial processes, are emerging. This potential change in energy use or change in the composition of energy required could alter the viability of certain cogeneration technologies.

A sound knowledge of the barriers that a new technology will face in the market is the first step in developing an effective project strategy. The identified market barriers encompass a wide range of problems—business, government policy, institutional, regulatory, financial, environmental, economic, and technological. After reviewing the barriers and market data, there appears to be a unique need for small, packaged gas turbine cogeneration systems.

### *Technological constraints*

Cogeneration under the power maximization mode requires high-pressure and high-temperature system parameters. High-pressure boilers, turbines, and accessories are not available in sufficient quantities indigenously. Turbines at high pressure are presently imported. There is also a considerable technological gap between the various advanced configurations and systems available in the developed countries. Table 5 (see next page) indicates the various technologies that are available abroad. There is a need to identify areas of research and development in the various cogeneration technologies required in the country.

### *Financial constraints*

One of the major problems for a firm interested in cogeneration is the relative capital intensity of a cogeneration system. The capital cost of a cogeneration system may range from $500–$1000/kW of installed capacity for oil and gas

**TABLE 5.** Status of cogeneration technologies available abroad

| Type of technology | State-of-the-art | Number of design options | Fuel |
|---|---|---|---|
| Steam turbine | Current | 10 | Petroleum boiler fuel |
| Steam turbine | Current | 10 | Coal |
| Diesel, high speed | Current | 2 | Petroleum distillate |
| Diesel, low speed | Current | 1 | Petroleum boiler fuel |
| Gas turbine combined | Current | 4 | Petroleum distillate |
| Steam turbine | Current | 1 | Petroleum distillate |
| Steam turbine | Advanced | 10 | Coal derived boiler fuel |
| Diesel, high speed | Advanced | 10 | Coal (AFB)* |
| Diesel, low speed | Advanced | 1 | Coal derived |
| Diesel, low speed | Advanced | 2 | Coal derived distillate |
| Gas turbine | Advanced | 1 | Coal derived boiler fuel |
| Gas turbine | Advanced | 5 | Coal (pulverized) |
| Gas turbine | Advanced | 5 | Petroleum boiler fuel |
| Gas turbine | Advanced | 2 | Coal derived boiler fuel |
| Gas turbine, indirect | Advanced | 4 | Coal (gasifier) |
| Gas turbine, closed cycle | Advanced | 3 | Coal (PFB)** |
| Gas turbine, closed cycle | Advanced | 5 | Coal (AFB) |
| Steam-injected gas turbine | Advanced | 5 | Coal derived boiler fuel |
| Steam-injected gas turbine | Advanced | 2 | Petroleum boiler fuel |
| Steam-injected gas turbine | Advanced | 2 | Coal derived boiler fuel |
| Steam-injected gas turbine | Advanced | 2 | Coal (PFB) |
| Combined cycle | Advanced | 2 | Coal (AFB) |
| Combined cycle | Advanced | 3 | Petroleum derived |
| Combined cycle | Advanced | 3 | Coal derived |
| Combined cycle | Advanced | 1 | Coal (PFB) |
| Combined cycle, indirect | Advanced | 2 | Coal (AFB) |
| Fuel cell, low temperature | Advanced | 2 | Petroleum distillate |
| Fuel cell, low temperature | Advanced | 2 | Coal derived distillate |
| Fuel cell, high temperature | Advanced | 2 | Petroleum distillate |
| Fuel cell, high temperature | Advanced | 4 | Coal derived distillate |
| Fuel cell, high temperature | Advanced | 1 | Coal gasifier |
| Sterling | Advanced | 2 | Coal derived distillate |
| Sterling | Advanced | 2 | Coal gasifier |
| Thermionics | Advanced | 2 | Coal derived boiler fuel |
| Thermionics compound cycle | Advanced | 3 | Coal derived boiler fuel |
| Steam turbine bottoming | Current | 10 | By-product heat |
| Organic ranking bottoming | Advanced | 3 | By-product heat |

*Atmospheric fluidized bed; **pressurized fluidized bed.
*Source*. Department of Electronics, USA.

systems to $1000–$1500/kW for coal, wood, or biomass systems. When in times of high interest rates and credit restrictions this capital intensity makes the financing of such systems a major consideration in their successful development. Where the firm's overall economic picture limits its ability to use the tax benefits associated with such projects, third-party ownership is the only answer in India.

Hence, the industries find it difficult to raise resources for the incremental cost of setting up a cogeneration system with the objective of selling surplus power to the utilities. The tax and duty structure on the capital equipment used for the cogeneration facility is not as attractive as in the case of other non-conventional energy sources. Liberal credit facilities such as concessional interest rates and larger repayment period should be provided to industries to encourage cogeneration.

### *Legislative constraints*

At present, there is no legal framework for the purchase of surplus cogenerated power in India unlike in the US. In US, it is mandatory for public utilities to buy the energy generated by the cogenerator at the avoided cost under the Public Utility Regulations Policies Act (PURPA). Avoided cost is the incremental cost to the electric utility that the utility will either generate itself or purchase from elsewhere if it did not purchase from the cogenerator. Very few SEBs have encouraged cogeneration. In fact, the self-generated sales tax imposed by the state tax authorities has acted as a disincentive for industries to opt for cogeneration. Except for two or three SEBs, all the other utilities do not have any arrangements for wheeling and banking of cogenerated power. It is important to have long-term purchase contracts between the SEBs and cogenerators for purchase of surplus power to encourage industries to opt for cogeneration under the power maximization mode.

### *Pricing policy and cost considerations*

One of the most crucial factors in promoting cogeneration relates to agreement on the tariff policy. There is no clear pricing policy for purchase of power. Utilities, while carrying out their long-term planning exercise, must consider cogeneration option as a source of firm power supply in relation to conventional power generation options. The tariff for cogenerated power should therefore be set at the avoided cost for new capacity added for meeting base-load demand.

Except for two or three SEBs, the utilities in India do not have any formal policy for purchase of cogenerated power. Ideally, the utilities must pay the marginal cost or the avoided cost of their own power generation or purchase from any source other than the cogenerator. Utilities, however, under the principles of grid discipline, consider the short-run marginal costs (fuel and operating costs). This makes the cogeneration option unviable and, therefore, deters investment by the industries. However, under the power maximization option, incremental capacity is added by the industry with the sole objective of supplying to the grid. Therefore, the cogenerator must be paid both capacity and variable costs.

### *Technical barriers and problems of parallel operations*

The quality of electric power has always been a major problem with the utilities in India. High voltage fluctuations, frequency variations, and frequent power failures are factors that need to be taken care of. They add to the cost of the cogeneration plant.

The cogenerator may have a slightly different set of concerns, such as safety, interconnection costs, production of the cogeneration system, power costs, and impact on production.

Utility system reliability is also affected by the location of the cogeneration interconnection on the utility system. If the interconnection is at a transmission level, then interruptions of service have greater potential impact than those at a distribution level. The utility may require even more stringent protection requirements from cogenerators connected to the transmission system to protect *downstream* customers of the cogenerator.

Another consideration is the generator size rather than the plant load and the load on the utility life. This will usually result in more stringent protective requirements, since the utility and the cogenerator will again seek to protect utility and customer equipment from service disruptions.

Harmonic currents are another problem. Harmonic currents occur at frequencies other than the desired 50 Hz of the power signal. When transmitted along power transmission and distribution lines, these harmonics distort the power signal.

Both the cogenerator and the utility need to protect their respective personnel and facilities from injury and damage caused by mis-operation of generator. This protection often utilizes automatic equipment to detect and isolate the faulty sections of a circuit so that the remainder of the network can continue to deliver power without interruption.

When cogenerators are present, several areas of utility planning may be affected because of the dispersed locations of the cogenerators. These impacts may show up in the following areas—voltage regulation, load restoration after interruptions, and sufficient circuit capacity.

Utilities will need to account for deviations from their expected load surveys and from load factors caused by dispersed generation. These form the foundation of utility planning. Dispersed generation, which is usually not planned for, displaces some electrical demand as well.

## The two-part tariff system

The Ministry of Power, under its policy to encourage private sector participation in power generation, has introduced a two-part tariff system in order to guarantee returns to the private investors. The first part of the tariff ensures recovery of fixed costs (including returns) based on performance at normative parameters.

The second part ensures meeting of variable expenses, based on units of electricity actually supplied. Incentives will be provided for the achievement of efficiency levels higher than the normative parameters. Once the rate for sale of power is fixed, no limits of any sort will be put on actual profits earned by a generating company. The system also provides for the signing of a Contractual Agreement laying down rates for the bulk sale of power by a generating company to an SEB for a specified period.

## ECONOMIC CONSIDERATIONS

Steam turbine generators can help save substantial amount of energy in cogeneration systems. However, these plants require greater capital expenditures than plants which supply only low pressure process steam. This incremental capital investment must be justified by the reduced annual operating costs. Generally, a capital budgeting decision analysis is made to determine if the venture meets the company's requirement for return on investment or payout. Likewise, any additional investment for a larger or more efficient cogeneration alternative *versus* a smaller system must also meet management's requirements for return on investment or payout.

The first step for an economic evaluation of cogeneration systems is normally to determine the course of action, which involves minimum capital expenditure. This is the *base case.* For a new plant, this would be low-pressure boilers for process heat and no cogeneration. For an existing plant, the base case might be the do-nothing alternative.

Several cogeneration alternatives might be proposed. These might include various throttle pressures, the use of a condensing section, or a combined steam and gas turbine. The base case and the cogeneration alternatives should then be developed to determine the estimated performance data and equipment ratings. The next step would be to convert these data into terms of cold cash, i.e., initial investment cost estimates for each alternative and annual operating costs. When these data have been developed, a return or payout evaluation is made. If several cogeneration alternatives meet management's capital budgeting criteria, then each increment of additional investment should be evaluated. The final decision would be to select the alternative with the highest increment, which meets the return or payout criteria.

### Investment cost data

The incremental investment costs due to cogeneration should be the focus of evaluation of a cogeneration system. The incremental cost data represent the differences in cost between a low pressure process-boiler plant and a cogeneration plant with steam conditions of 60 bars, 415 °C turbine inlet, and a 3.5 bar exhaust. All cases include 50% spare boiler capacity. The low-sulphur coal and residual oil include costs of the particulate removal system.

It has to be noted that these costs exhibit a substantial economy of scale penalty for plant sizes less than 90 tonnes/hour. In larger plant sizes, the incremental investment costs are Rs 300 000–360 000/kW, with an additional Rs 450 000/kW added for dust collection systems.

Investment costs in terms of Rs/kW will vary significantly with steam conditions. For example, a 15 bar process pressure, instead of 3.5 bar, would increase investment costs by approximately 50%.

## Annual operating costs

The focus of developing annual operating costs should be on any differential costs due to cogeneration. Normally, these include costs of fuel, power, labour, maintenance, cooling water, and boiler make-up water.

To illustrate these calculations, evaluations of a 160 tph plant size have been made for residual oil and coal. In addition to the 60 bar cogeneration system, plants that throttle pressures of 85 and 100 bars have also been considered. The premises used in evaluating annual operating costs are shown in Table 6.

An example of the calculation of annual operating costs for a residual fuel case with a purchased power rate of Rs 2.25/kWh is shown in Table 7. Also included in this table is a summary of calculations of gross payout. However, discounted rate of return (DRR) is given on the incremental investment for cogeneration cases. Gross payout is defined as:

$$\text{Gross payout} = \frac{\text{Incremental investment}}{\text{Gross annual savings}}.$$

The DRR calculations can be made using the after-tax discounted cash-flow analysis method. The parameters used in these calculations are:

- income tax rate—50%;
- depreciation—28 years, sum-of-the-years method;
- investment life—25 years; and
- local taxes and insurance—2.5%.

The typical minimum acceptable DRR values for industrial firms are in the range of 15–25%. All three cogeneration alternatives mentioned earlier would pass such a criterion. The next step would be to determine DRR values for the

**TABLE 6.** Premises of economic evaluation of cogeneration plants

| Category | Premise |
|---|---|
| Annual operation | 8400 hours/year |
| Fuel costs | |
| Residual oil | Rs 6.50/(10000) kcal (HHV) |
| Coal | Rs 1.25/(5500) kcal (HHV) |
| Purchased power cost | Rs 2.25/kWh |
| Annual maintenance cost | 2.5% of investment |
| Operating labour | |
| Process boiler cases | Base |
| Cogeneration cases | Base + Rs 9 000 000/year |
| Plant size | 160 tph process steam load |

***Note.*** Cost data for a hypothetical case.

**TABLE 7.** Summary of annual operating costs and an example of economic evaluation of cogeneration plants

| Annual operating costs | Base case | 60 bar | 85 bar | 100 bar |
|---|---|---|---|---|
| Fuel consumption (Gcal/hour) | 120 | 144 | 150 | 153 |
| Net power (kW) | (440) | 23720 | 29500 | 31600 |
| Annual costs (Rs in lakhs) | | | | |
| Fuel | 6549.38 | 7864.75 | 8197.73 | 8349.08 |
| Power | 83.16 | (4483.08) | (5575.50) | (5972.40) |
| Labour | Base | 10 | 10 | 10 |
| Maintenance | 9 | 11 | 12 | 12 |
| Total | 6641.54 | 3432.67 | 2644.23 | 2398.68 |
| Annual savings | Base | 3208.87 | 3997.31 | 4242.86 |
| Gross payout (years) | Base | 2.22 | 2.21 | 2.23 |
| DRR (%) | Base | — | — | — |

***Note.*** Figures in parentheses indicate earnings due to export of surplus power to the grid.

incremental investment for the higher pressure cases against the 60 bar cogeneration case. For some companies, the higher pressure would have an acceptable return; for others, it would be unacceptable.

Another important parameter not illustrated here would be the hour/year of operation. When a cogeneration system is operated at base load to serve continuous heat and power requirements, it generates maximum savings in annual operating costs. When the cogeneration system serves non-continuous loads (5 or 10 shifts per week) and/or seasonal cyclic loads, the annual savings will be differences in cost between a low pressure process-boiler plant and a cogeneration plant with steam conditions of 60 bars, 415 °C turbine inlet, and a 3.5 bar exhaust. All cases include 50% spare boiler capacity. The low-sulphur coal and residual oil include costs of the particulate removal system.

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Investment costs in terms of Rs/kW will vary significantly with steam conditions. For example, a 15 bar process pressure, instead of 3.5 bar, would increase investment costs by approximately 50%.

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Another important parameter not illustrated here would be the hour/year of operation. When a cogeneration system is operated at base load to serve continuous heat and power requirements, it generates maximum savings in annual operating costs. When the cogeneration system serves non-continuous loads (5 or 10 shifts per week) and/or seasonal cyclic loads, the annual savings will be diminished. Therefore, cogeneration systems in these applications are more difficult to justify.

## FINANCING COGENERATION PROJECTS

Cogeneration projects generally involve investment in capital equipment to produce electricity and thermal energy. Such investments produce revenues from the sale of electricity and thermal energy, or reduce the operating costs for the purchase of such energy. The financing of a cogeneration project is, therefore, similar to the financing of any capital-intensive project. Revenues from the sale of products from the cogeneration project (or the cost reduction resulting from the use of these products) must be sufficient to provide for the operating expenses and produce sufficient returns for the investments made in the project by the financing sources.

### General considerations

While cogeneration projects exhibit a tremendous diversity in project size, scope, ownership, financing method, and the amount of financing required, the following issues must be considered in developing the optimum financing approach.

1. *Credit worthiness.* What is the credit rating of the various parties involved in the cogeneration project, and what is their capability to generate the necessary financing?
2. *Type of financing.* What are the different possible methods for financing the project, and what could be the roles of the various parties in developing the financing?
3. *Financing sources.* What are the major sources for the funds required for the cogeneration project, and what portion of the total funds will come from each source?
4. *Risks and risk sharing.* What are the major financial risks presented by the cogeneration project, and who will share the risk and in what proportion?
5. *Ability to utilize tax benefits.* Can project participants take advantage of the available tax benefits, and what is the optimal allocation of tax benefits to the various participants? This might be beneficial under the New Economic Policy.
6. *Requirements of financing sources.* What requirements will the major financing sources impose upon the project, and how can these be satisfied?

It is important for project developers to pay adequate attention to all these issues in order to develop the financing plan, which will provide adequate resources for the project and sufficient sharing of risks and benefits to the various project participants.

## Financing sources

Although there are several industrial financial institutions, financing of cogeneration projects requires some special considerations such as cogeneration co-developers and build, own, operate, and transfer/build, own, and operate/build, operate, and transfer (BOOT/BOO/BOT) schemes. Cogeneration project developers (these may include engineering firms and/or equipment suppliers) will find that a number of different sources are available for financing their projects. Projects may be financed exclusively from one of these sources, or through a combination of different sources. It is also important to recognize that some of these financing sources will provide equity financing as well as debt to the project. An evaluation of which financing source would be the most appropriate for a particular project depends on the type of financing commitments, the terms of financing, the size of financing required, and the approach of the financing organization to risk containment and risk sharing. A discussion on some of the common financing sources is provided below.

### *Commercial banks*

Commercial banks are likely to be one of the most common sources for financing cogeneration projects. In particular, medium-to-large commercial banks are increasingly interested in alternative energy projects and are now convinced that cogeneration projects are attractive for conventional bank financing. For large projects, banks may form a consortium to develop the needed financing. The terms and conditions of commercial banks can vary significantly from project to project, and may include fixed or variable interest rates, repayment terms ranging from 5 to 15 years, project security requirements ranging from project equipment to other assets of the developer or sponsor, and various types of guarantees or contractual requirements. Commercial banks may finance construction projects also, either during the construction stage or after it is complete. Normal public sector banks like the State Bank of India, Industrial Development Bank of India, Industrial Finance Corporation of India, and others come under this category.

### *Insurance companies*

Insurance companies have traditionally been excellent sources of financing capital projects and may be interested in cogeneration. Insurance companies are generally willing to provide longer terms for financing, ranging from 15 to 20 years. They may be willing to take equity positions in certain projects, in addition to providing debt financing. Insurance companies are also likely to be willing to take somewhat higher risks than conventional banks, as long as appropriate rewards are available to them to cover the risks taken. These are the Life Insurance Corporation, Group Insurance Corporation of India, and others.

### *Third-party financing*

This type of financing is being practised mostly in the US. Considering the high interest rates prevalent in India, a number of third-party financing companies have been established for the explicit purpose of financing cogeneration projects. The idea of BOOT/BOT/BOO is also applicable under similar conditions. These companies have access to a number of different financing sources and are actively searching for cogeneration projects with the right types of economic returns. Third-party financing has ranged from less than $1 million to several million dollars for some projects. Quite often, these third parties have technical knowledge of cogeneration, as well as expertise in the institutional aspects of cogeneration, particularly with respect to state and federal regulations and contract negotiations with utilities and other parties. Also, these developers can take advantage of the available tax benefits and are able to pass some of the benefits to the project sponsors. Third-party financing companies are willing and interested in equity positions in projects, and there have been projects selling the project outputs to an industrial firm and/or a utility.

These types of developers are quite willing to structure innovative financial arrangements that may benefit all the parties involved in the cogeneration project. During the last several years, an increasing number of large organizations are expressing interest in third-party financing, and are actively searching for opportunities to finance cogeneration projects. This is now actively being considered in India also.

### *Individual investors*

Owing to a number of tax benefits offered by cogeneration projects, individual investors represent a potential financing source. Limited partnerships can be structured to provide tax benefits, cash flows, and potential long-term value to individual investors. Individual investors will generally require a greater return on their equity, but at the same time they are more willing to take greater risks and to receive their returns over a long term, as long as some immediate tax benefits are available in the short term.

### *Equipment manufacturers*

Manufacturers of cogeneration equipment such as boilers, turbines, and generators are increasingly looking to the cogeneration market for the sale of their products. They have recognized that financing such equipment may increase their chances of making the sale to project developers or sponsors. Manufacturers are, therefore, increasingly providing finance to cogeneration projects. Some manufacturers have even set up cogeneration financing companies, specifically offering equity and debt financing to cogeneration projects. In the process, they have become *full service* companies, which will provide a range of services including feasibility analysis, design, financing, construction, operation, and maintenance. Several firms in India are now considering this seriously. In fact, two turbine manufacturers are already having small-scale power plants under their scheme.

### *Architect/engineering firms*

A number of large architect/engineering firms, who have traditionally provided services to central station power generation markets, are now turning their attention towards the cogeneration market. They too have recognized that if they offer other services such as financing, their chances of making a sale may increase. These types of organizations are willing to take equity positions in projects and are interested in providing a number of different services besides design and construction management.

### *Industrial development authorities*

For cogeneration projects owned by municipal or public authorities, tax-exempt financing through industrial development banks may be feasible. The advantage of such financing is that the debt cost may be reduced substantially over conventional financing methods. The ability to qualify for tax-exempt financing depends on the satisfaction of a number of complex state and central government regulations.

## Requirements of financing sources

The cogeneration project developer or sponsor must be aware of the major requirements of the financing sources. The most obvious and the most critical requirement of a financing source is that the basic project is economically viable. In other words, the project must generate sufficient cash flow to pay all the project expenses, plus the interest and debt payments, as well as a return on the investment of the equity participants. The second major requirement is that the project risks are minimal. Most financing organizations want a reasonable assurance that the project interest and debt payments will be met in the future. Cogeneration projects involve a number of risks. If these risks are considered to be significant, then the financing organization will insist on recourse financing, requiring the project sponsor to commit his other assets or resources as collateral for the project in case of default on debt payments. In order to minimize the risks and provide protection against long-term uncertainties, financing organizations will generally require long-term protection. In other words, it will be important for the developer to obtain contracts for his purchase of fuel, as well as for the sale of the thermal and electric energy, such that the long-term prices and costs are bound within certain limits. If such contract protection cannot be obtained, financing sources may consider the project inherently risky, and may require other types of protection to assure that the interest and debt repayments will be met by the project developers.

In risky situations, financing sources will look for a debt coverage ratio of the order of 200%, i.e., the anticipated net cash flows (project revenues minus all project expenses) should be twice the anticipated interest payments and debt repayments. If the anticipated revenues and costs are guaranteed through contract protection, then the debt coverage ratio can be smaller.

A final requirement for financing sources is the sharing of benefits proportional to the risks. Higher the risk transferred to it, greater the returns expected by the financing source. Therefore, projects involving substantial risks may elect to obtain equity participation by various types of organizations or to establish limited partnerships with investments by individual investors, who are willing to take higher risks.

### *Risks and risk containment*

A cogeneration project is subject to a number of varied risks. Some of these are summarized below.

1. *Design and technology.* Will the proposed design and technology perform as anticipated at the appropriate efficiency levels?
2. *Construction costs.* Will the project be constructed within the estimated costs?
3. *Timing and completion.* Is the project subject to significant delays or will it be completed within the schedule as anticipated?
4. *Fuel supply and cost.* Will the required fuel supply be available in sufficient quantities and without significant escalation in cost?
5. *Sale prices and quantities.* Will there be an adequate market for the sale of cogeneration products, and will the market accept the prices that are anticipated?
6. *System performance.* Will the various components of equipment in a cogeneration project perform as anticipated, and produce the required outputs for the designated level of inputs?
7. *Operating costs.* Are the operating costs subject to unforeseen escalations?
8. *Financing costs.* Are the financing costs controlled, or is there a risk that these costs might escalate if economic conditions change?
9. *Tax regulations.* Will the anticipated tax benefits actually be available, or would changes in tax regulations remove some of these benefits?

10. *Regulatory and environmental risks.* Are there any significant changes in environmental or other regulations anticipated during the life of the project that may make the project unacceptable to regulatory authorities?

While all these risks cannot be totally eliminated, it is important to limit or contain these risks so that both the project developer and the financing organization are comfortable with the level of risk faced by each, relative to the returns anticipated. Typical methods that have been used to contain risks are summarized below.

1. *Design and technology risks.* Obtain quality participants, who are knowledgeable regarding cogeneration technologies and design considerations.
2. *Construction costs.* Obtain insurance coverage against cost escalation, or assign fixed price contracts with the construction management firm.
3. *Timing and completion risks.* Obtain insurance protection or contract protection to assure that the project is completed on time.
4. *Fuel supply and costs.* Sign long-term contracts with fuel suppliers.
5. *Electric and thermal sales.* Obtain long-term contract protection by signing contracts with the purchasers of electricity and thermal energy.
6. *System performance.* Obtain performance guarantees from the manufacturer, or insurance coverage from appropriate insurance companies.
7. *Operating costs.* Obtain recognized and reputable design engineers, who are knowledgeable of the appropriate technologies being used.
8. *Financing costs.* Negotiate appropriate arrangements with the financing sources so that escalations of financing costs are minimized.
9. *Tax regulations.* Keep track of current trends in regulatory initiatives at both the central and state levels.
10. *Environmental and other regulations.* Keep track of the appropriate regulatory changes anticipated, and obtain reputed organizations knowledgeable of environmental and other regulations relevant to the cogeneration project.

It is important to recognize while addressing risks and risk containment methods that the requirements of the project developer or sponsor and those of the financing source may, at times, conflict. For example, the financing organization would require a long-term contract for the sale of electricity to the utilities; while from a project developer's viewpoint, the cost of negotiating such a contract may be significant, both in terms of legal fees and the time required to negotiate such a contract. The ENRON project in Maharashtra is a case in point. The negotiation of a fixed price construction contract may increase construction costs because the construction management organization will load the risks of the fixed price onto its pricing. Owing to such potential conflicts, it is important that the project developer/sponsor work very closely with the financing organization in structuring the project and in designing the risk containment methods, so that the overall project risks are minimized at the lowest possible cost to the developer and the financing organization.

## CONCLUSION

Cogeneration is a useful technology in reducing waste and in conservation of resources. However, its application needs careful evaluation because of its complexity. In spite of the barriers and constraints, there is a need to enhance its penetration for the overall benefit of the society.

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## 4

# Thermal gasification of biomass—potential, problems, and research needs

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## INTRODUCTION

Biomass is defined as living matter or its residues, and is therefore a renewable and perpetual resource. Worldwide photosynthesis activity is estimated to store 17 times as much energy as is annually consumed by all the nations in the world. Even when energy requirements for collection, processing, and conversion to other useful forms are taken into account, biomass still assures a bright future from the energy point of view.

Biomass can be broadly classified into three categories: (i) woody biomass; (ii) agricultural and agro-industry residues; and (iii) animal wastes. Woody biomass obtained from natural forests, man-made forests, agro-forestry, etc. is a highly valued commodity and has diverse uses such as timber, raw material for pulp and paper, plywood, pencil, and match sticks. Jute sticks are harvested at the village level and are essentially used either as fodder or as cooking fuel. It is common to find that residues are often burnt in the fields as a method of disposal. Biomass residues such as saw dust, rice husk, groundnut shells, bagasse, bamboo dust, coir pith, and coffee husks are products of agro-industries and are available in large quantities at a given site. These residues frequently cause disposal problems. The most prominent animal waste is cattle dung, which is used as fuel or fertilizer in rural areas. Urban wastes such as municipal solid waste (MSW) can also be considered as biomass. Animal and urban wastes are usually characterized by a large moisture content.

Methods of converting biomass into useful forms of energy can be broadly classified into biochemical and thermochemical. The biochemical route of conversion of biomass to other useful forms is a low energy process and relies upon the action of bacteria, which degrade complex molecules of biomass into simpler ones. The production of biogas, a mixture of methane and carbon dioxide, from animal dung by means of anaerobic digestion is an important example of this process. The biochemical methods of conversion have been discussed elsewhere in this publication.

In the thermochemical method, biomass is subjected to a high temperature, and depending on the quantity of oxygen supplied, processes such as pyrolysis, combustion, and gasification occur. Direct burning of biomass in stoves and open fires is an example of combustion, in which the supply of oxygen is generally higher than that required stoichiometrically. Under conditions of lower rates of oxygen supply, pyrolysis and gasification occur. Preparation of charcoal from wood and incineration of MSW are examples of pyrolysis. Under certain conditions of temperature and oxygen supply, a gaseous mixture rich in carbon monoxide and hydrogen, referred to as producer gas, is formed. This process is called thermal gasification and is discussed in detail in the following sections.

## THERMAL GASIFICATION

In what is known as a gasifier, a solid fuel is converted to a gaseous fuel (producer gas) by a series of thermochemical processes such as drying, pyrolysis, oxidation, and reduction. If atmospheric air is used as the gasification agent, which is the normal practice, the producer gas will consist mainly of carbon monoxide, hydrogen, and nitrogen. A typical composition of the gas obtained from wood gasification on volumetric basis is as follows:

carbon monoxide—18–22%;
hydrogen—13–19%;
methane—1–5%;
heavier hydrocarbons—0.2–0.4%;
carbon dioxide—9–12%;
nitrogen—45–55%; and
water vapour—4%.

The calorific value of this gas is about 900–1200 kcal/Nm$^3$. This gas can be used for generation of motive power either in dual-fuel engines or in diesel engines with some modifications. Engines operating on a spark ignition system (e.g., petrol engine) can be made to run entirely on producer gas, whereas those using compression ignition systems (e.g., diesel engine) can be made to operate with about 60–80% fuel oil replacement by the gas. The gas can also be burnt directly for applications such as cooking in hotels, production of hot water and steam in small industries, and drying of a variety of agricultural and industrial products.

As mentioned earlier, complete combustion takes place with excess air or with at least 100% theoretical air, whereas gasification takes place with excess carbon. The gasification of solid fuels containing carbon is accomplished in an air-sealed, closed chamber, under slight vacuum or pressure relative to the ambient pressure. The fuel column is ignited at one point and exposed to the air-blast, while the gas is drawn off at another location. Depending upon the positions of air inlet and gas withdrawal, with reference to the fuel bed movement, three broad types of gasifiers have been designed and operated to date. These are: (i) updraft; (ii) downdraft; and (iii) cross-draft gasifiers (Figures 1–3).

In the updraft gasifier, air is introduced below the grate to provide the oxygen for partial combustion of carbon immediately above the grate. The hot gaseous combustion products proceed upward through a reduction zone of incandescent charcoal, where heat is consumed to gasify carbon and produce hydrogen and carbon monoxide. Then the gases transfer heat to the raw fuel, first pyrolising it and then drying it. The gas exits above the upper zone or at a side port near the top of the gas producer. The exiting gas has a very low solid particulate content.

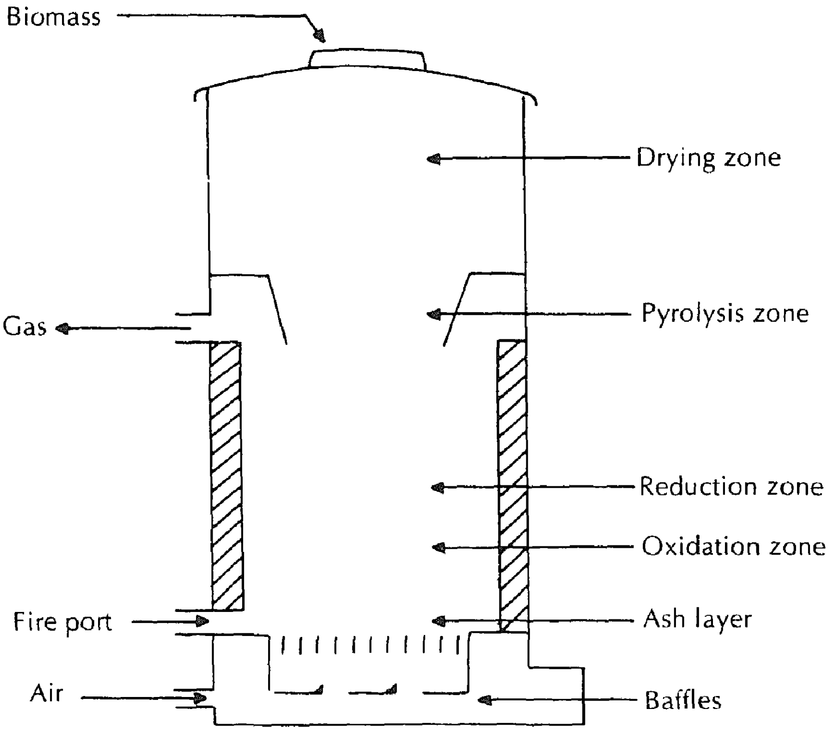

**FIGURE 1.** Schematic diagram of an updraft gasifier.

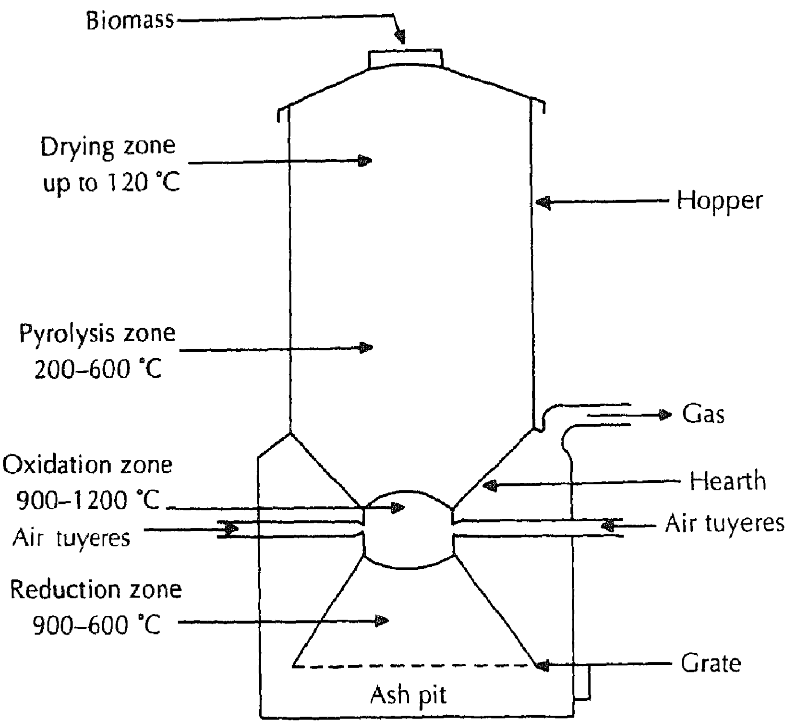

**FIGURE 2.** Schematic diagram of a downdraft gasifier.

If the fuel is raw biomass, it will have a high vapour content of condensable unburnt pyrolysis products (tars) and water.

In the downdraft gasifier, air enters through radial tuyeres near the top of the firebox. The partial combustion takes place in the zone in front of the tuyere openings. The heat generated pyrolysis the fuel immediately above and hot gases proceed downward through the firebox construction and exit through the grate. The throat (constriction) forces the raw gases to pass through a high temperature zone so that most of the tars can be cracked into gaseous hydrocarbons, thus producing a relatively clean gas.

In the cross-draft gasifier, air enters through a water-cooled nozzle mounted on one side of the firebox. The gas is produced in the horizontal zone in front of the nozzle and passes through a vertical grate into the hot gas port on the opposite side. Due to the short path length for gasification reactions, this type of gas producer responds most rapidly to changes in gas production. However, the cross-draft gasifier is not commonly used.

The downdraft gasifier, also called the co-current moving bed gasifier, is most commonly used for engine application because of its ability to produce relatively clean gas. However, the presence of throat poses problems of fuel movement.

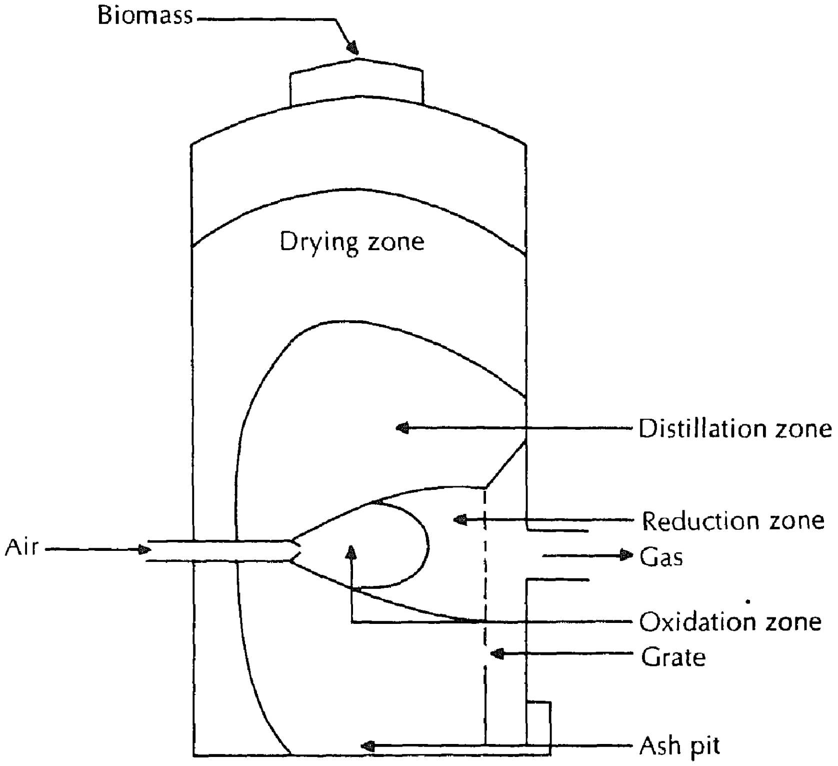

**FIGURE 3.** Schematic diagram of a cross-draft gasifier.

Of late, the so-called throatless gasifiers have been developed at the Solar Energy Research Institute, Colorado, USA; Indian Institute of Science (IIS), Bangalore; Nimbkar Agricultural Research Institute (NARI), Phaltan; and Tata Energy Research Institute (TERI), New Delhi. For larger sizes, fluidized bed gasifiers and entrained bed gasifiers have also been considered.

A complete understanding of the various complex reactions occurring in a gasifier has not been possible so far. However, the following reactions explain the process of gasification fairly well.

$$C + O_2 \rightarrow CO_2 + 393\,800 \text{ kJ/kg mole (combustion)} \quad (1)$$

$$C + H_2O \rightarrow CO + H_2 - 131\,400 \text{ kJ/kg mole (water gas)} \quad (2)$$

$$C + CO_2 \rightarrow 2CO - 172\,600 \text{ kJ/kg mole (Boudouard reaction)} \quad (3)$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 + 41\,200 \text{ kJ/kg mole (water shift reaction)} \quad (4)$$

$$C + 2H_2 \rightarrow CH_4 + 75\,000 \text{ kJ/kg mole (methane reaction)} \quad (5)$$

The sequence of these reactions in a downdraft gasifier is shown in Figure 4. With the help of the above reaction scheme, and with a knowledge of the equilibrium constants, it is possible to predict the equilibrium composition of the gaseous products. The equilibrium composition for a given solid fuel depends upon the air supply per unit weight of the biomass. A dimensionless parameter, known as the equivalence ratio (ER), to characterize the air supply conditions, is usually defined as follows:

$$\text{ER} = \frac{\text{Weight of oxygen/Weight of dry fuel}}{\text{(Weight of oxygen/Weight of dry fuel) stoichiometric}}.$$

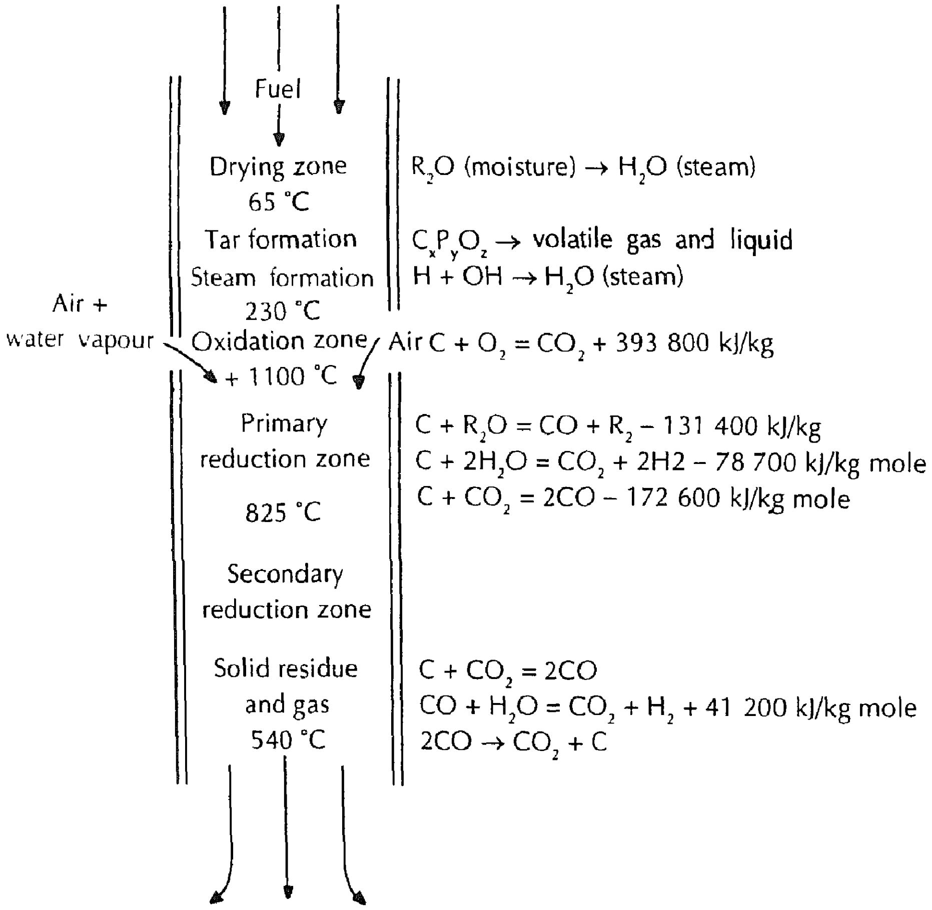
Fuel
Drying zone
65 °C
$R_2O$ (moisture) → $H_2O$ (steam)
Tar formation
Steam formation
230 °C
$C_xP_yO_z$ → volatile gas and liquid
H + OH → $H_2O$ (steam)
Air +
water vapour
Oxidation zone
+ 1100 °C
Air $C + O_2 = CO_2 + 393\ 800$ kJ/kg
Primary
reduction zone
825 °C
$C + R_2O = CO + R_2 - 131\ 400$ kJ/kg
$C + 2H_2O = CO_2 + 2H2 - 78\ 700$ kJ/kg mole
$C + CO_2 = 2CO - 172\ 600$ kJ/kg mole
Secondary
reduction zone
Solid residue
and gas
540 °C
$C + CO_2 = 2CO$
$CO + H_2O = CO_2 + H_2 + 41\ 200$ kJ/kg mole
$2CO \rightarrow CO_2 + C$

**FIGURE 4.** Sequence of reactions in a downdraft gasifier.

The denominator in the above equation is the oxygen required for complete combustion of the fuel and it varies from fuel to fuel. The mole fraction (or volume fraction) of the various components of producer gas as a function of ER is shown in Figure 5.

It is generally observed that for effective gasification, ER should be in the range of 0.2–0.4. Below an ER value of 0.2, pyrolysis predominates the process and above an ER value of 0.4, combustion predominates.

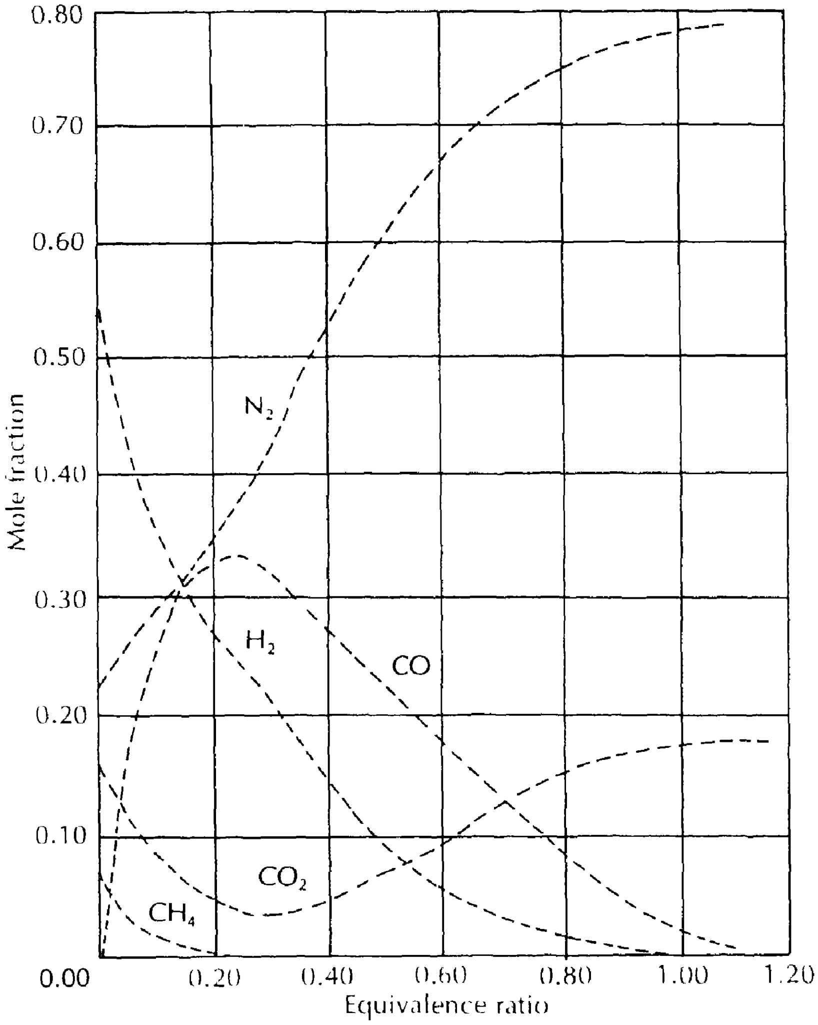

**FIGURE 5.** Equilibrium composition of producer gas.

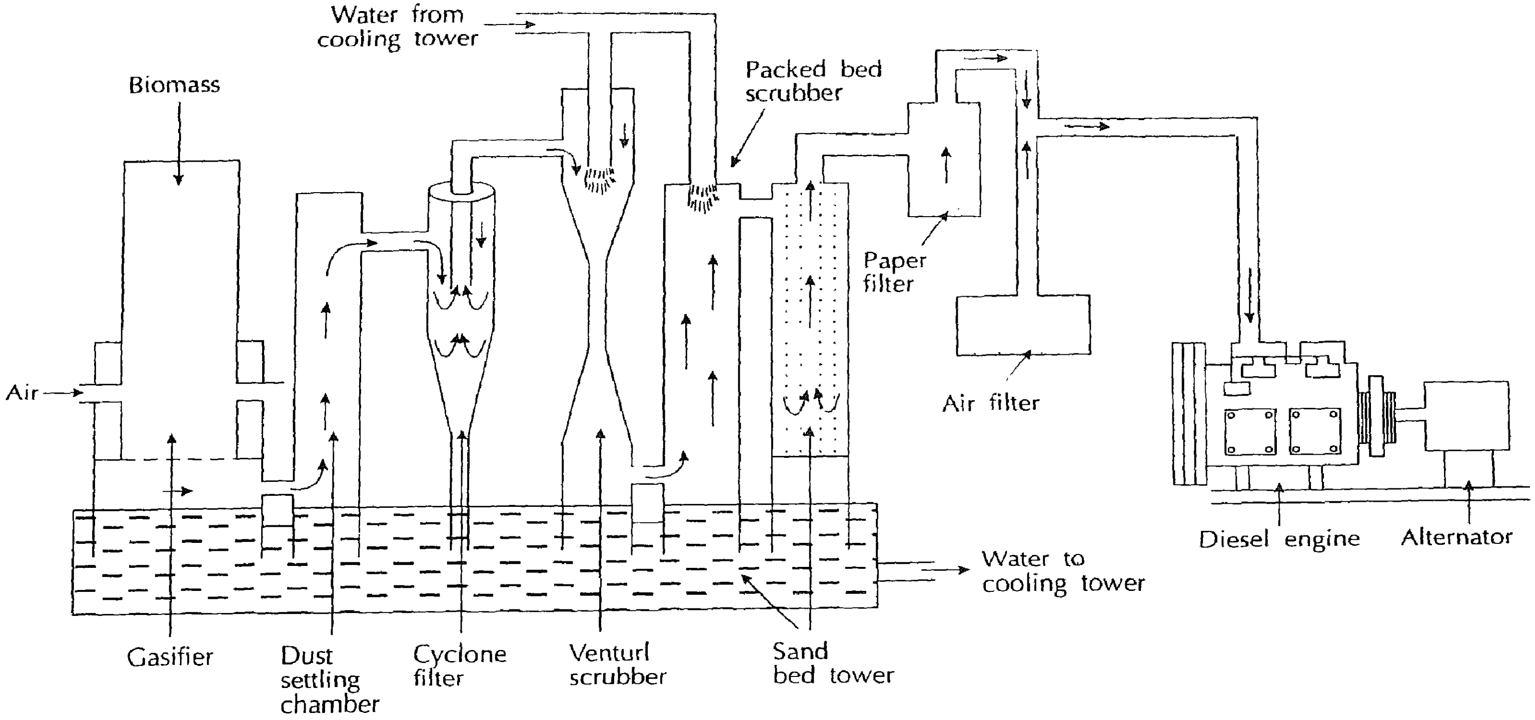

**FIGURE 6.** Gasifier for power generation.

In a real gasifier, however, the composition of the gas is far from the equilibrium value and is generally dependent on the gasifier design. Factors affecting the gas composition are temperature distribution in the fuel bed, average gas residence time, and the residence time distribution. These are in turn dependent upon the mode of air entry, dimensions of the gasifier, and heat losses to surroundings. Modelling of the various processes occurring in the gasifier requires not only a knowledge of kinetics but also an understanding of the heat and mass transfer processes occurring in the various zones of the gasifier.

In all the existing gasifier designs, the raw producer gas generated contains varying amounts of moisture, dust, char particles, and tar. The gases are also at a high temperature. Admission of hot gases into an engine results in loss of power and hence the gas has to be cooled. Also, the impurities present in the gas are detrimental to the operation of internal combustion (IC) engines and hence the gas has to be cleaned before admitting into the engines. No standard has been evolved yet to determine the degree of purity required for engine operation, but a tar content of less than 100 $mg/Nm^3$ is generally acceptable. The conditioning of raw producer gas for use in IC engines usually consists of: (i) removal of larger char particles; (ii) scrubbing of gas to remove tar; (iii) cooling the gas; (iv) removal of moisture; and (v) removal of fine dust particles.

These processes are accomplished in a gas cooling and cleaning train such as the one shown in Figure 6.

Any carbonaceous matter can be gasified in principle. But from the point of view of operational reliability, some fuels are better than others. In general, fuels with low ash content such as charcoal, wood, and coconut shells are extremely suitable for continuous and reliable operation. Commercial gasifiers have generally avoided the use of high ash or the so-called slagging fuels. However, the successful operation of rice hull gasifiers for years in Italy and China, for example, shows that it is technically feasible to utilize even problematic biomass residues for gasification. In recent years, R & D efforts mounted at some Indian research institutes have resulted in gasifier prototypes, which can use a variety of biomass residues. The gasifier design developed by TERI can use several biomass residues in briquetted form (apart from firewood chips). The NARI has developed a gasifier design for sugarcane leaves and the IIS, Bangalore is currently engaged in gasification of powdery biomass.

## POTENTIAL OF BIOMASS GASIFICATION

Several studies have been undertaken in recent years to estimate the potential for biomass utilization in general and for biomass gasification in particular. It has been calculated that, even taking into account the demand for fodder, etc., the biomass available in the country (excluding animal residues) can optimistically support electrical power plants aggregating to a total of 17 000 MW.

Woody biomass can be gasified without any major problems and there are about four commercial manufacturers of gasifiers at present. The Ministry of Non-conventional Energy Sources has installed more than 400 small wood gasifier systems, mainly in Gujarat and Karnataka in the last few years. Almost all these are 3.75 kW (5 HP) irrigation pumping systems installed in rural areas. Larger systems of 100 kW capacity have also been installed in Arunachal Pradesh and Port Blair. Unfortunately, estimation of the availability of wood exclusively for gasification purposes can be quite tricky. The general situation of extensive deforestation is not conducive to utilization of wood for gasification purposes except in places such as Arunachal Pradesh, Jammu and Kashmir, Madhya Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Orissa, Sikkim, Tripura, and the union territories of Andaman and Nicobar Islands, where wood is in excess of local consumption at present. However, considerable amount of firewood is presently consumed inefficiently in various applications; some of which are listed below:

- production of hot air for tea drying in the southern tea estates;
- cardamom curing;
- stifling of cocoons in the silk industry;
- production of plaster of Paris from gypsum;
- heating applications in several small industries;
- large-scale cooking in hotels, hostels, hospitals, etc.; and
- cremation purposes.

There is enormous scope for introducing gasifier technology in these areas. It offers scope for reduced firewood consumption and pollution. In the case of India, which is primarily an agricultural country, agro and mill residues offer a large scope for utilization for gasification purposes. Mill residues such as saw dust, bamboo dust, rice husk, coir pith, and groundnut shells can be utilized for electricity generation or cogeneration employing gasifier technology. The country-wide availability of some of these residues has been estimated (Table 1).

If one takes into account residues such as mustard stalks, arhar stalks, and jute sticks, the availability would be even higher. From these figures, it is apparent from the resource availability point of view that there is a significant, if not overwhelming, potential for utilization of biomass residues for gasification.

The next criterion for evaluating the potential of utilizing biomass is its economics. A biomass gasifier system should be economically viable in order to compete with commercial energy delivery systems. This topic has also been studied extensively in recent years. Our studies on the economics of small wood

**TABLE 1.** The country-wide availability of some agro and mill residues

| Residue | Availability (million tonnes/year) |
|---|---|
| Rice husk | 29.32 |
| Maize cobs | 2.51 |
| Groundnut shells | 2.23 |
| Bagasse | 57.31 |
| Coconut shells | 0.88 |
| Coconut husk | 1.07 |
| Cotton sticks | 2.73 |

gasifier systems for irrigation pumping show that due to (i) cost of wood, (ii) number of operating hours, (iii) cost of diesel, and (iv) capital cost of gasifier systems, they are not economically viable at this point of time in many parts of the country. On the other hand, the use of biomass gasifiers for thermal applications and electricity generation seems to be promising. The cost of electricity generated would be about Rs 2/kWh and is generally competitive with diesel electricity in many locations. In favourable locations, where biomass is available at no or negligible cost, the cost of generation could be even lower than that of conventional electricity. The costs per million kcal of heat delivered for some fuels, including producer gas, are given in Table 2.

**TABLE 2.** Cost per million kcal of heat delivered for some fuels

| Fuel | Calorific value | Unit cost | Cost per capita |
|---|---|---|---|
| Diesel oil | 10700 kcal/kg | Rs 7.26/kg | Rs 678.50 |
| LPG | 11642 kcal/kg | Rs 6.55/kg | Rs 562.60 |
| Producer gas | 1100 kcal/Nm$^{3*}$ | Rs 0.52/Nm$^3$ | Rs 472.70 |

*Assuming a firewood cost of Rs 1.2/kg and a specific gas production of 2.3 Nm$^3$/kg.

It is apparent that producer gas from firewood or briquettes is the lowest cost option. Thus, while the physical and economic potential seems to be quite attractive, there are several hurdles—most of them related to technology—in realizing a large national programme for promotion of gasifier systems. These are discussed briefly in the following section.

## PROBLEMS AND RESEARCH NEEDS

Biomass gasification has a history of over 140 years. During the Second World War, an estimated 821 587 vehicles were running on producer gas and most of our present knowledge about gasification originated from developmental activities carried out during this period. Due to low oil prices in the post-war period, interest in gasification reduced drastically and funds were not available for further R & D. After the oil shock of 1970s, there has been a renewed interest in gasification of biomass, but this has again vaned in recent years after the recovery of oil prices. However, one cannot emphasize enough regarding the need for sustained R & D efforts in gasification, considering that the oil reserves are finite whereas the biomass resources are renewable and local.

Major problems of utilizing biomass for gasification are the ones related to operational reliability. For continuous and reliable operation, there should be a continuous flow of gases and biomass. But it has been found to be hindered mainly by two processes: (i) clinker formation and (ii) bridging of fuel. All biomass fuels contain ash (mineral matter) to a lesser or greater extent. The ash content varies from as low as 0.1% in some wood varieties to as high as 23% in rice hulls. The ash does not take part in the gasification process, but it experiences high temperatures during its travel through the various zones of the gasifier, particularly the combustion and reduction zones. At high temperatures, ash tends to melt and forms a molten slag, which subsequently agglomerates and forms huge lumps (clinker) above the grate. If the biomass has large quantities of ash, and if the ash melting points are low and its residence time in the high temperature zone is high, clinker formation invariably occurs, blocking the production of gas. The crux of the problem is that high temperatures and high fuel residence times are essential for the operation of gasifier. The problem of ash clinkering can be solved by resorting to efficient ash removal systems. Such systems, however, are not yet standardized. They also add to the total cost and complexity of the system and are usually advocated only for large-sized systems. Development of efficient, low-cost, and reliable ash removal systems is definitely an area worth concentrating on.

Bridging or arch formation occurs typically just above the combustion zone, under conditions not yet fully explored. The fuel in the immediate vicinity of the air tuyeres is consumed rapidly and a hollow space is formed above the air entry zone. The arch so formed is sufficiently strong to stop the biomass above from falling into the combustion zone. With no fuel supply and only air supply, the gas quality deteriorates rapidly until the production of gas is completely stopped. Sometimes the arch can be broken by vigorously shaking the gasifier or by poking the fuel bed with a rod but in some cases it may be very difficult to break it. If the bridging occurs too often, the gasifier would need constant attention which is highly undesirable. What is worse is that the arch formation is not easily detectable and only an experienced person can infer it either by the sound of the engine (in the case of gasifier based power plants) or by visual observation (if such facility is available). The factors causing arch formation seem to be many, some of them being (i) shape and size of the fuel, (ii) void fraction, (iii) geometry of the gasifier, (iv) design of the air inlet, and (v) nature of the fuel itself. A systematic study of the flow of biomass inside the gasifier under various conditions and for different biomass fuels has not been carried out so far and should be the subject of future R & D efforts.

A fundamental problem related to the design of the gasifier is the high degree of empiricism. Most of the design data such as selection of throat diameter (or diameter of the combustion–reduction zones in the case of throatless gasifiers), number and diameter of nozzles, position of air inlet with respect to grate, geometry of the fuel hopper, and insulation requirements (if any) are limited to the experience acquired during the Second World War. There have been no or very few attempts to find a rational and theoretical basis for selection of the various dimensions required to fabricate a gasifier. Strictly speaking, the presently available design data are applicable where charcoal or wood is used as gasifier fuel. Some norms had been laid down for specific gasification rate [the amount of gas produced per hour per unit cross-sectional area expressed in $Nm^3/(hour)(cm^2)$], based on experience with wood or charcoal gasifiers, though they are not always valid. For example, a minimum specific gasification rate of about 0.9 $Nm^3/(hour)(cm^2)$ had been recommended for throated downdraft gasifiers; but it has been shown that with proper insulation, specific gasification rates as low as 0.03 $Nm^3/(hour)(cm^2)$ can be achieved.

A vast amount of data exists on the physical and thermochemical properties of various biomass fuels. But there had been no attempts to utilize them in developing design methods for gasifiers. It is not even clear if they can be effectively utilized for designing gasifiers. Thus, the development of engineering design methods for gasifiers should form an important topic for future R & D studies.

Several biomass residues, except wood, have very low bulk densities in their natural form. Also, the availability of most of these biomass residues is seasonal. Hence storage of these residues is a process in which the bulk density can be increased significantly, thereby lowering the storage requirements. Experience shows that several biomass residues in briquetted form can be used in the same gasifier, eliminating the need for different designs of gasifier for different fuels. The method of using a briquetting–gasification route seems to be highly promising, but the overall economics of the technology would depend upon the scale of operation and cost of producing briquettes. The subject matter of briquetting has not been studied systematically so far and there is a need to develop efficient methods of briquetting biomass. Biomass briquettes, apart from being used in gasifiers, have the potential to be used as fuel for industrial purposes or for cooking.

Raw gases produced in the gasifier have to be invariably cleaned before admitting them into IC engines. The degree of purity of gases necessary to make them engine-quality gases seems to be highly debatable. Guidelines as to what should be the allowable limits of tar, dust, and moisture in the gases have not yet been worked out. It is an arduous task to develop such guidelines as the contaminants of the gases have to be artificially controlled for a long time to study their effect on the engine performance with prolonged use. However, as long as the allowable level of contaminants is not spelt out, the design of the cooling and cleaning equipment would remain highly arbitrary as is the case at present. Also, sufficient data on the solubility of tar in water are not available, making the design of the scrubbing columns highly subjective. To ensure continuous flow of gases through the cooling and cleaning train, it is necessary that the overall pressure drop across the set-up remains constant and as low as possible. The use of porous beds for removal of dust and moisture, as is common in many installations, is hence undesirable as the pressure drop across such beds would keep increasing gradually as the beds absorb moisture and other contaminants, resulting in a gradual lowering of diesel replacement value.

A gasifier when used in conjunction with a diesel engine is essentially a device for saving diesel and the dependence on diesel is still substantial. Petrol engines, however, can be made to run completely on producer gas, albeit with a loss of power. However, engines cannot be started with gas, and diesel or petrol must be used for starting. The use of petrol engines is not common in rural areas. Further, petrol is more expensive than diesel. From these considerations, it seems highly desirable to develop engines starting on diesel and running on 100% producer gas. This means that engines with the combined features of compression ignition and spark ignition would have to be developed. Some efforts in this direction have been made though no commercial prototypes have been produced so far. A promising application of gasifiers is in the area of biomass-based cogeneration. A schematic diagram of a biomass gasifier-based cogeneration system for the tea industry is shown in Figure 7. Another system for production of decentralized power, using steam-injected gas turbines, is shown in Figure 8. These systems are only conceptual as yet and R & D efforts should be directed towards developing and demonstrating suitable prototypes. Recent field experience on gasifier systems showed that there are serious material failure problems, especially in the air nozzles and in the firebox region. It appears that the operating life of most of the existing gasifier designs is limited to about 1000 hours. It is thus important to find suitable solutions for this problem.

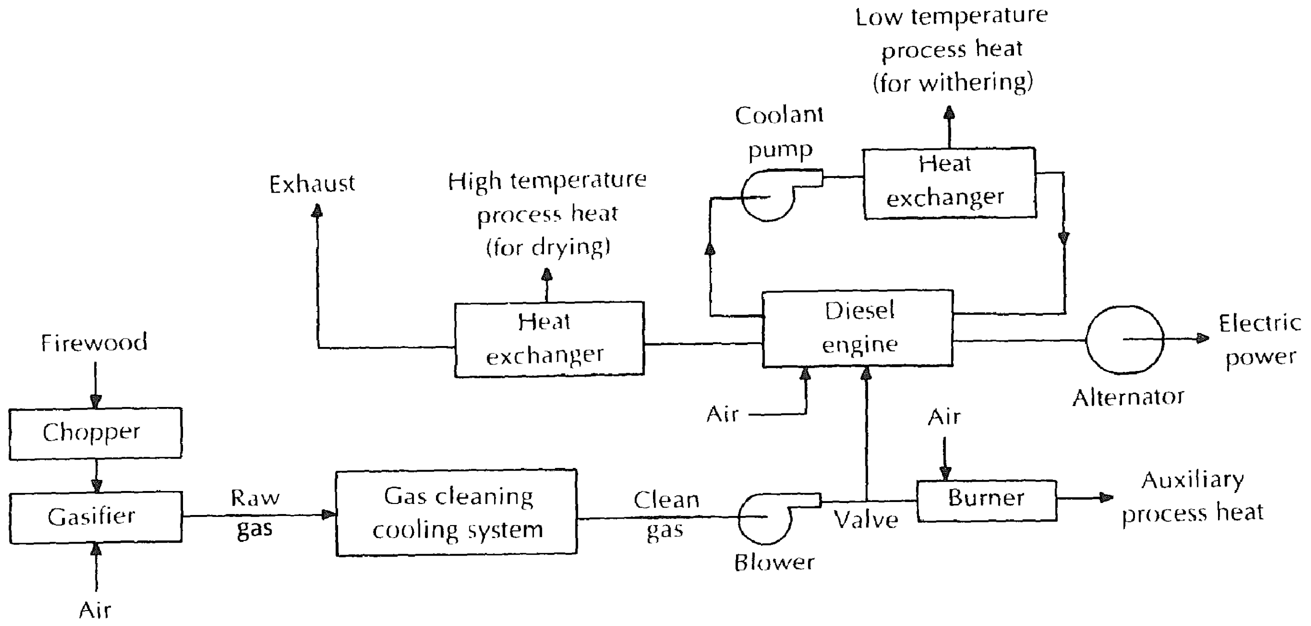

**FIGURE 7.** Biomass gasifier-based cogeneration system for tea industry.

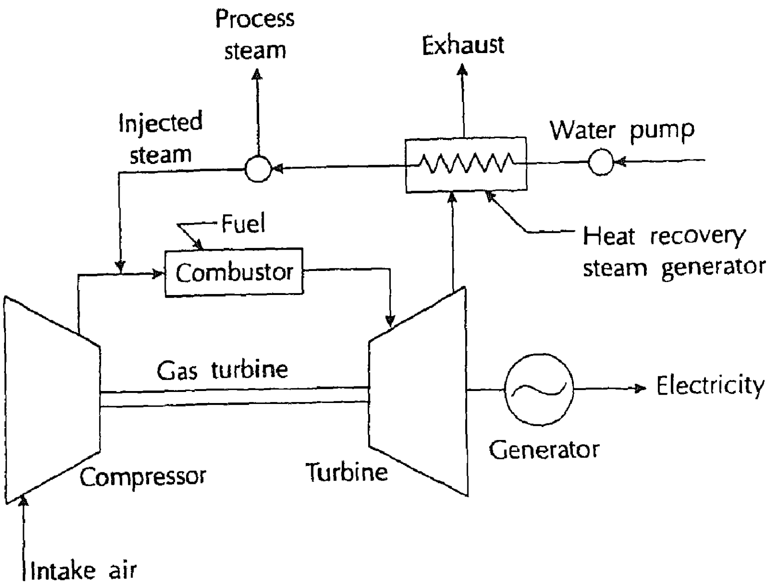

**FIGURE 8.** Steam injected gas turbine (SIGT).

## CONCLUSION

To sum up, R & D efforts in the highly promising area of biomass gasification have thus far been quite insignificant compared to the complexity and diversity of problems to be solved. Hence the importance of sustained efforts in R & D in biomass gasification and related fields cannot be emphasized enough.

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# 5

# Maximization of energy utilization by heat recovery

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## INTRODUCTION

It is most unwise to jump headfirst into heat recovery capital investment once the decision to save energy has been made. In the evangelical zeal of the moment, it is only too easy to make a serious error of judgement in the choice of heat recovery equipment.

The first step in any sound energy conservation programme should be the alteration of company policy and administration so that new ideas can be absorbed. This must start with acceptance by the top management of the fact that an energy-saving policy is a sound financial investment, and be followed by the percolation of this view through to the rest of the employees. It is at this stage that an energy manager is appointed and an energy audit initiated.

Results of the energy audit should show that a reasonable proportion of energy can be saved, without capital being spent, by mere good housekeeping, an improved and more worthwhile maintenance programme, and an optimization of plant processes. (The running of the plant is often found to have veered well away from its original design parameters.) A sound knowledge of energy audit and the quality and quantity of the heat sources and sinks would help in reducing the risk associated with capital investment.

Investment can be made in a wide range of energy-saving products. For instance, if savings need to be made on heating, and the building ventilation system constitutes a number of small, individual ducting systems, it may be best to install an energy management/optimizer system. However, recovery and re-use of waste heat can also be a feasible alternative.

## HEAT RECOVERY

Once a waste heat source has been identified, it must be matched with a simultaneous heat demand, which is of comparable size and is not too distant. (The cost of insulating the connecting ductwork can outweigh the original fuel savings.) From then on, it is a matter of balancing the scales of equipment capital cost and its heat recovery efficiency within a given payback period. The first assessment of cost is of the capital cost of equipment; but this can sometimes be dwarfed by installation costs, which in the case of retrofits can go up to four times the equipment cost.

The use of heat recovery efficiency alone in a calculation is also an oversimplification. Other factors to be accounted for in a calculation of total efficiency are the total time (for example, hours/day) that the equipment will be running, maintenance costs, downtime of the equipment if it should breakdown, and regular maintenance of the plant.

This analysis is only pertinent if the engineering parameters of plant and equipment are the only factors to be considered. It ignores the human element involved in plant maintenance; there often isn't any! This is particularly true in commercial buildings where heat recovery units can be installed in the air-handling plant. It is all too easy to forget the equipment once it is installed within the ductwork and remains unseen.

Most heat recovery equipment are intrinsically reliable, but none of it is truly maintenance-free and will deteriorate if cleaning and some replacement of parts are not done. It is therefore common practice for purchasers to opt for sacrificing a certain percentage of efficiency for simplicity and easy maintenance.

## SPECIFIC INSTALLATION PROBLEMS

No two installations will have the same set of problems and requirements, and a correct installation will be based on the solution unique to that particular set. The construction, ownership, and the uses to which it is put are the next set of factors to be considered while making the choice of heat recovery equipment.

### Construction

Some of the questions that usually arise regarding construction are listed below.

1. Where are the heat sources and sinks?
2. If they are far apart, can the connecting duct be insulated sufficiently to prevent excessive heat loss?

3. What headroom is available for heat recovery and ancillary equipment, and how can it all be supported?
4. How much accessible will the equipment be when installed?
5. What is the physical state of the heat source—liquid or gas?
6. Is the heat source contaminated?
7. If so, will the contaminant be deleterious to the heat sink, corrode or foul the heat recovery unit?
8. What is the temperature and moisture content of the heat sink?
9. Are the flow rates of the heat source and sink comparable?
10. If the source and sink are part of a production process, could the heat recovery installation affect quality or production rate?
11. Will control or bypass systems be needed with the equipment?

## Cost

There are two rather unrelated factors that will affect cost. First, will the equipment be installed during original building or refurbishing? As pointed out earlier, installation costs of a retrofit can be four times the cost of the equipment. Second is the legal/legislative requirements. There is, as yet, no legal requirement to install energy-saving equipment.

## Application

There are a number of equipment types available and each unit possesses its own peculiar set of properties, which makes it useful for particular installations. Each type can be produced in a variety of materials and temperature ranges to extend its usefulness.

### *Exhaust gas boilers on diesel gensets*

Every diesel genset (DG set) exhausts high temperature waste gases to the atmosphere. This precious energy can be recovered and put to use for process heating or absorption cooling and even for power generation. The installation of exhaust gas boilers downstream of the DG set can enhance the system efficiency by as much as 20%.

For industries such as cement or steel, where steam is not required, waste heat can be gainfully harnessed for additional power generation using a closed loop system. Where steam is not necessarily the process heat medium, Thermax can custom build other forms of exhaust gas heat recovery systems such as hot air, hot water, and hot oil generators.

The design options for the exhaust gas boilers include natural circulation, two-drum water tube or fire tube boilers. Alternative options are for forced circulation, single-drum, plain tube or finned tube boilers. Thermax builds such boilers for smooth integration into DG sets of various makes, for example, Caterpillar, Wartsila, Skoda, Kirloskar, Nigata, Cummins, and Fuji.

*Salient features*

- Natural circulation fire tube or water tube design to suit the DG set
- Compact, custom built units
- Suitable for handling flue gases from heavy fuel fired DG sets
- Designed to handle fluctuating steam loads
- Quick steaming characteristics

### *Exhaust gas boilers for gas turbines*

In any gas turbine, only 25–35% of the heat input from the fuel is converted to useful energy. The balance heat is lost in the exhaust gases. To enhance system efficiency, it is essential to recover this heat either for process use or for power generation. Most gas turbines operate in the cogeneration or combined cycle mode by installing downstream heat recovery units. Since very large exhaust gas volumes are involved, a water tube type design is preferred both in natural circulation and forced circulation. The use of extended surface tubing makes the boiler very compact and allows for retrofit options. Gas turbines are characterized by fast load variations and the boiler is designed to withstand and respond to the rapid pressure, temperature, and flow gradients.

The exhaust gases have a high oxygen level. Therefore, steam generation can be increased by firing fuel into the exhaust gases without combustion air being supplied. This provides for greater operational flexibility.

*Salient features*

- Use of suitable extended surface tubing to maximize heat transfer
- Suitable for any pressure temperature steam generation
- Forced or natural circulation designs
- Duct burners provided to generate additional steam
- Multi-pressure steam generator for maximum heat recovery

### *Dichromate roasting kilns*

The production of dichromate involves high temperature roasting of chromite ore in a rotary kiln. The flue gases preheat the feedstock charged into the rotary kiln and are exhausted from the kiln at a medium temperature (450–500 °C). These gases contain a large volume of dust. The heat can be recovered in specially designed three-drum water tube natural circulation boilers. The steam generated in the boiler is used for process requirements. The special feature of the design is wide tube pitching so that low gas velocities are maintained to prevent tube erosion and choking in the gas path.

Soot blowing devices are also incorporated to clean heat transfer surfaces. Hoppers are provided with rotary airlock valves to periodically discharge the collected dust.

*Salient features*

- Natural circulation water tube design
- Three-drum geometry handles high temperature dust-laden gases
- Optimum tube size and pitch to prevent choking
- Provision of soot-blowing device to ensure efficient heat transfer
- Adequately sized dust collection hoppers

### *Exhaust gas boilers for glass melting furnaces*

Waste gases leaving glass melting furnaces are at high temperatures (1200–1400 °C) and contain a high carry-over of silicates and alkalies besides residues from heavy oil firing. These waste gases have a high potential for heat recovery.

A radiation or regenerative type of recuperator is placed in the gas path to preheat combustion air to enhance furnace performance. The gases leaving the recuperator can be cooled further in a waste heat boiler to generate low or medium pressure steam.

A water tube boiler is the best suited option as it can handle dust-laden gas without choking. The on-line cleaning ability of the heat transfer surfaces ensures effective heat recovery. These boilers can be of natural or forced recirculation design.

*Salient features*

- Compact two- or three-drum natural circulation design
- Optimum tube size and pitch to avoid choking
- Low gas velocities to avoid erosion of tubes
- Provision of soot blowing devices to maintain surface cleanliness

### *Process integrated waste heat boilers for sulphuric acid plants*

The double conversion double absorption process for the manufacture of sulphuric acid from elemental sulphur generates considerable heat in the exothermic conversion of sulphur to sulphur dioxide and sulphur trioxide gases. Since the catalyst vanadium pentoxide is optimal at about 440 °C, coolers in the form of boilers and gas-to-gas heat exchangers to remove the heat of reaction are essential. The steam generated by the boiler is used for melting sulphur and for driving the main blower. This steam can also be used for power generation or exported to a steam user.

Depending on pressure and temperature requirements, a smoke tube or water tube design in a natural circulation configuration is adopted for the boiler. Suitable cast iron gilled elements are arranged to form the economizer and superheater sections to complete the steam circuit and provide the right temperature conditions. Thermax Ltd has the experience and expertise to engineer and construct complete heat recovery systems for sulphuric acid plants.

*Salient features (water tube design)*

- Compact design with the correct selection of gilled elements
- Suitable for high pressure applications
- Generously sized steam water drum with adequate number of risers and downcomers to obtain optimal circulation ratios
- Specially designed castings to withstand acid corrosion
- Refractory brickwork/ceramic blanket with liners to minimize thermal stress

*Salient features (fire tube design)*

- Designed to withstand high gas pressures
- Option of internal bypass available
- Fully wetted tube sheets to prevent thermal stress
- Minimal refractory to reduce thermal inertia
- Less drum elevation for good circulation on the water side of the tube
- Fully shop-made pressure part assembly for quick site installation

### *Process integrated waste heat boilers for ammonia combustion*

The production of nitric acid/caprolactum is a two-stage process—high temperature oxidation of ammonia followed by cooling of hot gases before they are absorbed to make the final product. The catalytic oxidation of ammonia at 950 °C results in emission of hot gases containing oxides of nitrogen, and then cooled to 250 °C for further reactions.

Specially designed boilers in a water tube configuration and having forced circulation are normally adopted for gas cooling. A vertical fire tube of natural circulation design can also be used depending on the pressure/temperature requirements of the process. Since the gas side pressures are as high as 5–7 bars, the mechanical parts need to be carefully selected.

In the water tube design, helical pancake coils are located in the pressure vessel. The stacking generally consists of pre-evaporator, superheater, main evaporator, and economizer surfaces. Access to heating surfaces is gained, if possible, by means of the vessel's girth flanges. Heating surfaces are not normally drainable. An external steam drum is connected to the evaporator by means of riser and downcomer circuits.

### *Salient features (water tube design)*

- Gas-tight construction with stainless steel material
- Wall cooling coils to protect the shell
- Water tube of forced circulation design is fitted with heating coils to prevent dew point corrosion
- Special ammonia burner design for uniform combustion reaction over the catalyst

### *Process integrated waste heat boilers for steam reforming unit*

All cracking reactions such as the steam reforming process in ammonia, methanol, hydrogen, and ethylene plants result in flue gases and reformed gases with high temperatures. The reformed gases, at 900 °C and 20–30 bars pressure, have to be cooled before they go to the next stage. The inherent sensible heat in flue gases leaving the reformer also needs to be recovered to increase the thermal efficiency of the system.

The energy extracted from the flue gas and reformed gas is utilized for steam generation, superheating of steam, feed water preheating, combustion air preheating, and feedstock preheating. The medium-to-high pressure steam generated is used as process steam for the cracking process and also for running compressor drive turbines.

The choice of a fire tube or water tube design generally depends on plant size, process knowhow, and steam conditions. Auxiliary firing equipment is provided in the flue gas steam for start-up and to balance energy needs. It is normal practice to install a fire tube boiler on the reformed gas path and an extended surface heat recovery unit on the flue gas path.

### *Salient features (fire tube design)*

- Uniform gas velocity
- Short gas residence time
- Special design of tube sheets to withstand stress
- Fouling of high heat flux area avoided due to settling of sludge and other particles at the bottom of the boiler shell
- Less drum elevation for good circulation on the water side of the tube

### *Process integrated waste heat boilers for sponge iron plants*

Sponge iron is produced by reduction of iron with a reducing agent. The established processes are for coal- and gas-based plants. Coal-based plants have a rotary kiln, where coal, iron ore, and additives are fired. The flue gases, generated by the reaction, pass through a post-combustion chamber, where the combustible off-gases and particles are burnt. The hot, dust-laden flue gases enter a specially designed waste heat boiler, which generates medium or high pressure superheated steam.

The gas-based route involves cracking of natural gas in a reformer. The cracked gas leaving the reformer is fed into the shaft kiln for producing sponge iron. The technology available for the gas-based sponge iron plants uses two means of waste heat recovery for energy optimization. The air recuperation route is used for the MIDREX process. In the steam generation route for the HYL process, waste heat boilers are specially designed to handle high pressure and high temperature gases to produce steam to generate power.

The enormous reduction in the temperature of iron ores in the coal-based process results in the emission of a large volume of high temperature, dust-laden gases in the range of 1000–1200 °C with loads as high as 40 g/Nm$^3$. Since the process does not require steam, the waste energy recovered is converted to electrical power.

The heat recovery package involves a gas-tight, water-cooled membrane panel for radiation-pass for cooling the gas to 750 °C, thereby reducing the possibility of slag deposition on the heat transfer surface. A plain tube superheater is used for achieving the required steam temperatures. This is followed by an evaporator and economizer. A forced or a natural circulation system design can be adopted. A soot blowing system is used to periodically clean the heat transfer surfaces.

*Salient features*

- Natural circulation water tube design
- Gas-tight membrane panel construction for radiation pass
- Wide-pitched in its line geometry to prevent choking
- On-line soot blowing system
- Unheated riser and downcomer circuits to ensure good circulation
- Judicious selection of crossover temperature between the radiation pass and the superheater

### *Process integrated waste heat boilers for pyrite roasters*

Roasting of pyrite ores in a fluidized bed produces the oxide required to manufacture the primary metal. This oxidation process also produces flue gases containing sulphur dioxide at a temperature of 900 °C with a high dust load. These gases need to be cooled and dedusted for further conversion to sulphuric acid.

The cooling of gas is done by means of a specially designed water tube boiler. Waste gases enter either a large water-walled vestibule or a refractory-lined chamber containing the tubular bundles, arranged vertically and suspended in the gas flow path. The wide pitching and vertical tube geometry minimize choking of the gas path due to dust load and allows for effective gas cooling. These boilers are normally of the forced circulation design, which ensures that the heat transfer tubes are fully wetted. The high dust load in the gases requires the installation of an on-line tube cleaning facility. This is a hammering device, which is connected by cams to the coils, which are periodically vibrated to dislodge the dust into the hoppers. The dust is continuously removed by enclosed conveyors.

*Salient features*
- Water tube geometry to cater to high pressure steam generation
- The option of a membrane panel construction minimizes refractory work and makes the boiler compact
- Forced circulation design to ensure constant circulation ratio
- Adequate tube pitch to prevent choking of gas-path
- On-line dust cleaning facility

### *Process integrated waste heat boilers for smelters*

Smelting of copper and zinc generates high temperature dust-laden gases, which can be used to produce steam and thus improve overall energy balance for the process. About 35% of the heat input to the smelter can be recovered as steam. The waste gases coming from the furnace flow through a water-walled chamber (large membrane panel), where radiant heat is absorbed and some amounts of slag and dust settle down. This is followed by a convection section comprising vertical bare tube modules suspended in the gas path. Either a natural or forced circulation design can be adopted.

*Salient features*
- Water tube membrane panel construction to maximize radiant heat recovery
- Forced circulation design to ensure positive water circulation at all times and quick start-up
- Dust removal achieved by means of hammering devices
- Installation of shock tubes in the gas path before installing the other heat recovery bundles

### *Waste gas boilers for carbon monoxide gas*

Many chemical processes generate waste gases containing combustibles such as carbon monoxide, hydrogen, and methane. These can be efficiently burnt to produce steam for the process or for power generation. Typical examples of such sources of gas are in carbon black plants, fluidized crude cracking units, charge chrome furnaces, and lead–zinc melters. The variable content of carbon monoxide governs the calorific value of the gas.

Specially designed refractory-lined combustors are used for lean gas burning with provision for support fuel firing. The hot flue gases leaving the combustor either pass through a fire tube or water tube boiler, the choice being governed by the steam pressure and temperature requirement. A bare tube superheater is incorporated to achieve desired steam temperatures. Higher thermal efficiencies are achieved by installing an air preheater or condensate preheaters downstream of the economizer.

Depending on the particle carry-over, suitable soot blowing devices can be provided. A complete burner management system, along with boiler controls, forms the instrument package required to run the system smoothly.

*Salient features*

- Special refractory-lined combustor for burning of lean gas
- Tangential injection of lean gas into the combustor
- Adequately sized combustor for proper residence time to ensure complete burning of the gas
- Membrane wall water tube construction to minimize the refractory and to increase the radiant heat transfer

### *Waste gas fired boilers for hydrogen gas*

Hydrogen gas, a by-product in the caustic soda industry, is liberated during the electrolysis of brine. This gas has a high calorific value and is a clean fuel for steam generation. Tail gases in monoethylketone and formaldehyde plants are also rich in hydrogen gas and can be used as a fuel to produce steam.

Thermax Ltd has engineered a special boiler to effectively use the high calorific value of hydrogen gas. The boiler has a unique combination of water tube and fire tube designs. Hydrogen gas can be fired independently or in combination with a liquid or gaseous fuel. Considering the highly combustible nature of the gas, special safety features are in-built in the design. Special water seals, block and bleed valves, and a flame arrestor are incorporated in the gas train to prevent any explosion. In-built features of the boiler avoid stagnant flue gas pockets.

*Salient features*

- In-line layout of the radiation chamber and convection section to avoid stagnant gas pockets
- Panel membrane, natural circulation construction
- Design without refractory ensures quick start-up
- Water-cooled furnace walls to recover radiant heat
- Burner selection to fire a combination of fuels simultaneously or in isolation
- Fully shop-made radiation and convection assembly to ensure reliability

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# 6

# Methanogenesis

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## INTRODUCTION

Any waste or residue, in fact all organic matter left by itself under biologically open conditions, will undergo spontaneous biological degradation. This process is generally referred to as digestion. When this process occurs in the absence of oxygen, it is called anaerobic digestion. In nature, anaerobic digestion occurs at the bottom of stagnant lakes and swamps. In man-made systems, this process is used for sewage treatment of wastes and energy (biogas) production. Biogas is composed of methane, hydrogen sulphide, carbon dioxide, and carbon monoxide. Among these, methane is inflammable and a source of energy. The process of methane generation (biomethanation) was identified by an Italian physicist, Alessandro Volta in 1776. However, it took another 100 years to effectively use this process for waste treatment [1].

## BIOCHEMISTRY OF BIOMETHANATION

In fact, no known microbe can produce methane from substances other than acetate, carbon dioxide and hydrogen, methanol, formate, carbon monoxide, and some methylated amines. As the available substrates are much more complex, it is imperative to have a population of different groups of organisms, which can produce simpler end-products from these complex substrates. In practice, it is also necessary to have a group of bacteria capable of producing acetate, carbon dioxide, and hydrogen from the end-products of the complex substrates. There are three distinct trophic groups of microorganisms involved in the process of biomethanation [2]. They are hydrolytic fermentative microorganisms, acetogenic fermentative bacteria, and methanogenic bacteria.

## Hydrolytic fermentative microorganisms

The first fermentative or hydrolytic groups of organisms are able to attack polymeric molecules though they appear as solid material [3]. These microorganisms have elaborate hydrolytic enzymes, which hydrolyze polymeric substrates into low molecular weight material or even monomers, for example, proteins to amino acids, polysaccharides to oligo- and mono-saccharides, and lipids to free fatty acids. Though a diverse substrate specificity exists, many of these bacteria have a wide substrate range and short generation time. They, in competition with major fast-growing fermentative bacteria, the other predominant ones, though unable to utilize polymeric material, are able to take up smaller soluble molecules for their metabolism and growth [Figure 1 (a & b)]. As a result, short-chain fatty acids (VFA), i.e., with two to five (or more) carbon atoms, are produced. The primary acids produced are acetic acid, followed by propionic and butyric acid, and small quantities of formic, valeric, isovaleric, and caproic acids [4]. Ammonia, sulphate, iso-acids, and certain aromatic compounds are also produced from amino acids [Figure 1 (b)]. As many organic acids are produced during this step, it is often called acidogenesis [1]. The acidogenic population is by far the largest of the trophic groups of bacteria in anaerobic digestion [4]. Population of $10^8$–$10^9$ hydrolytic bacteria per ml of mesophilic sewage sludge has been documented by several investigators (Table 1) [5–7]. Enumeration studies of hydrolytic bacteria that utilize specific carbon substrates demonstrated $10^7$ proteolytic and $10^5$ cellulolytic bacteria in sewage sludge and $10^4$–$10^5$ hemicellulose-degrading bacteria in rumen digestion [7–9].

Another important aspect of hydrolytic fermentation is that many of these bacteria, in the presence of autotrophic methanogens and sulphate-reducing bacteria, produce hydrogen for the disposal of excess electrons generated during

**TABLE 1.** Bacterial population from anaerobic digesters

| Groups | Cells/ml |
|---|---|
| Total hydrolytic bacteria | $10^8$–$10^9$ |
| Proteolytic | $10^7$ |
| Cellulolytic | $10^5$ |
| Hemicellulolytic | $10^6$–$10^7$ |
| Hydrogen-producing acetogenic bacteria | $10^6$ |
| Homoacetogenic bacteria | $10^5$–$10^6$ |
| Methanogens | $10^6$–$10^8$ |
| Sulphate reducers | $10^4$ |

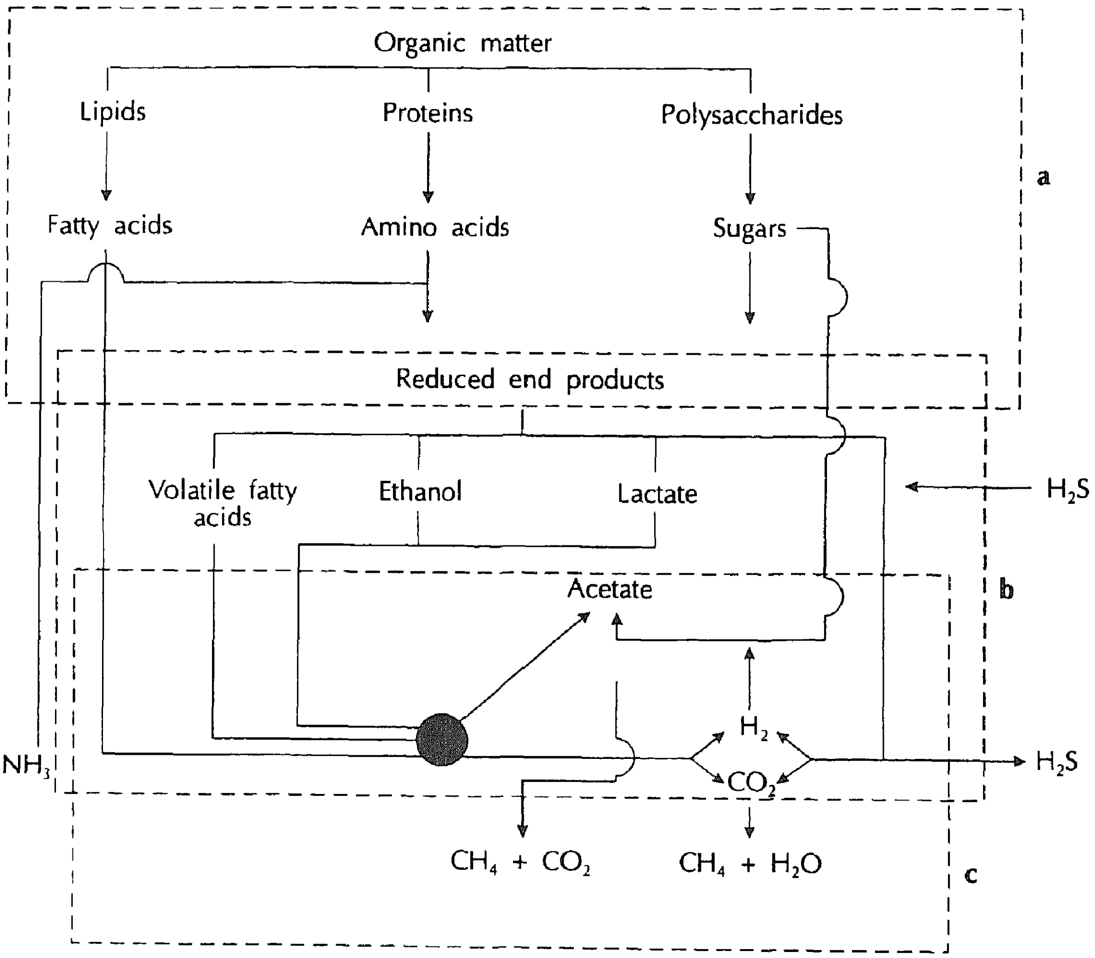

**FIGURE 1.** Actualized flowsheet of methanogenesis.
*Source.* Nyns E J. 1986. Biomethanation processes, p. 207. *Biotechnology.* Vol. 8, edited by J Rehn and G Road. Weinheim: VCH.

energy-yielding oxidation of organic material (Figure 1). However, accumulation of hydrogen due to inhibition of autotrophic methanogens results in thermodynamically unfavourable conditions for the disposal of electrons as hydrogen molecules. This will result in the formation of products such as propionate, butyrate, succinate, and ethanol, which will act as the hydrogen sink. Unionized organic acids, hydrogen ions, and hydrogens are inhibitory to other groups of bacteria, while the acidogenic population is much more tolerant to these intermediates [4]. Certain polymeric molecule-utilizing anaerobic bacteria are *Fibrobacter succinogens, Ruminococcus albus, Ruminococcus flavefaciens* [10], *Butyvibrio fibrisolvens, Prerotella ruminicola* [11] and *Selenomonas ruminatium* [12].

## Acetogenic fermentative bacteria

Acetogenic bacteria obtain their energy from the oxidation of organic acids, alcohols, and VFAs with more than two carbon atoms, for example, caproate, butyrate, and propionate. Individual species of acetogenic bacteria are usually very specialized and ferment only a limited number of simple compounds to acetate, formate, bicarbonate, and hydrogen [Figure 1 (b)]. These conversions are extremely sensitive to hydrogen and the growth of acetogenic bacteria, and can occur only at a partial pressure of hydrogen—less than $10^{-5}$ atmosphere [4]. Some acetogens also ferment xenobiotic compounds such as polyethylene glycol (PEG) and phenolic compounds [13–16].

Some acetogenic bacteria produce acetate from compounds such as trimethoxy benzoate, trimethoxy cinnamate, some methoxylated aromatics. Examples of some important acetogenic bacteria are *Acetobacterium woodii* [17], *Clostridium aceticum* [18], *Clostridium formicoaceticum* [19], *Eubacterium limosum* [20], *Sporomusa termitida* [21], *Acetogenium kivui* [22], *Acetoanaerobium noterae* [23], *Butyribacterium methylotrophicum* [24], and *Peptostreptococus productus* [25]. Some acetogens are found to dechlorinate tetrachloromethane through reductive process. A lot of potential exists for efficient exploitation of this capability in the degradation of such chemicals in industrial as well as municipal wastes [26].

The chemical free energy change is positive for most of these acetogenic reactions under standard conditions. The acetogenic bacteria suffer from a thermodynamic product inhibition by hydrogen [27, 28]. Hence, growth rate of the slowest growing trophic groups of anaerobic digestion is totally dependent upon the simultaneous removal of the reduced end-products such as acetate and hydrogen. For this reason, acetogens are always found in co-cultures with those bacteria (usually methanogens) which would provide them with favourable growth conditions while their metabolic partners are provided with carbon and energy sources [29].

## Methanogenic fermentative bacteria

Methanogenic bacteria (methanogens) are the ultimate trophic group in the process of anaerobic digestion. They produce the most reduced form of carbon, namely, methane. As stated earlier, methanogens cannot use the fermentation end-products of first trophic group of the anaerobic digestion process, i.e., hydrolytic fermentation, either for their growth or for methane production. They use terminal end-products of acetogenic fermentation, namely, acetate, formate, methanol, methylamine, and hydrogen and carbon dioxide as carbon and energy source [2]. A few methanogens derive their energy from carbon dioxide by reduction using hydrogen [Figure 1 (c)]. Autotrophic methanogens assimilate carbon dioxide as carbon source. The other microbial species, which are aceticlastic, chemo-organotrophic archaebacteria, split acetate into methane and carbon dioxide and obtain their energy [29, 1]. Acetate is an anion and when split into methane and carbon dioxide, it requires a pairing cation. When the pairing cation is either $NH_4^+$ or $H_3O^+$, bicarbonate and carbonic acid are produced. During carbonic acid formation, carbon dioxide escapes in the evolved biogas, ultimately resulting in alkalinity or reinforced buffering capacity to combat the acid produced by the previous groups [1]. In anaerobic digesters, more than 60% of the biological methane originates from acetate, thus aceticlastic methanogens perform the important ecophysiological function of carbon and electron removal while maintaining neutral pH [2].

Barker postulated that the pathway of methane formation was initiated by attachment of carbon dioxide to a carrier molecule and that all subsequent reduction steps involved one carbon intermediate attached to a carrier molecule [30]. The most thoroughly studied system is the reduction of carbon dioxide with hydrogen by *Methanobacterium thermoautotrophicum*. Its metabolism encompasses nearly the entire spectrum of reactions involved in methanogenesis. The central pathway is illustrated in Figure 2 (see next page). In the elucidation of this central pathway along with conventional co-enzymes, several surprising molecules were discovered. The enzyme-mediated reactions, which involve the six new co-enzymes, are only partially understood [31, 32]. Major taxonomic groups of methanogenic bacteria are isolated from various sources and they are *Methanosaeta soehngenii* [33], *Methanothrix* sp. [34], *Methanosarcina* sp. [35], *Methanosarcina mazei* [36].

## FACTORS AFFECTING BIOMETHANATION

Biomethanation as an industrial process is gaining importance and its success is dependent upon the control over a diverse microbial population and its biological activity. Besides microbial population, the environmental factors, which govern the process of methanogenesis, are anaerobiosis, temperature, pH, substrate composition, carbon:nitrogen (C:N) ratio, micronutrients, the presence or absence of toxic materials in the substrate biomass, and accumulation of inhibitory by-products or intermediates of the process.

### Anaerobiosis

Methanogenesis is a strict anaerobic microbial process. The major trophic groups and methanogens in this process die in the presence of oxygen. Though the major microbial activity in methanogenesis is anaerobic, the presence of aerobic and facultative anaerobic bacteria has been reported by many workers [37, 38]. The number of facultative anaerobic bacteria in piggery waste digesters was found to be the same as that of anaerobes [37]. These bacteria do not have any role in the main degradative reactions of digestion but play some role in general sugar fermentation. Most probably these bacteria have a role in the anaerobic digestion as scavengers of oxygen, reducing the system to be suitable for the growth of the methanogens [37]. Therefore, the requirement for anaerobiosis in digesters can be formulated in a dynamic way by minimizing the diffusion of air into the digestion liquor. Most of the digesters are designed in such a way that the ecosystem is closed to atmospheric air so that the microflora in the digester is not exposed to oxygen tension [1].

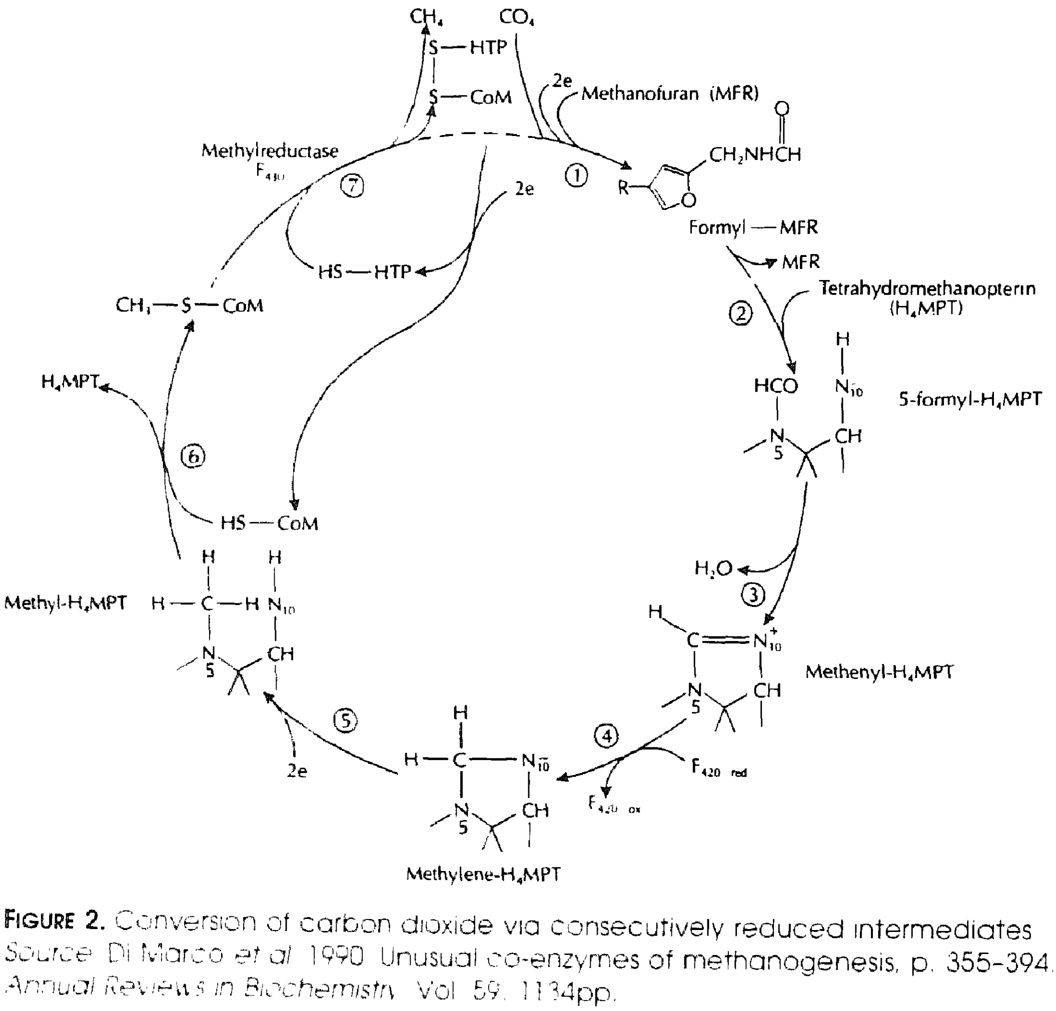

**FIGURE 2.** Conversion of carbon dioxide via consecutively reduced intermediates Source Di Marco *et al* 1990 Unusual co-enzymes of methanogenesis, p. 355–394. *Annual Reviews in Biochemistry* Vol 59, 1134pp.

## Temperature

Temperature in all microbial systems is known to enhance the microbial activity to a certain optimal level. Methanogenesis occurs practically in an optimal way in two ranges of temperatures. Mesophilic methanogenesis occurs at a range of 30–37 °C, and thermophilic methanogenesis between 50 and 65 °C. Adoption of mesophilic digester to thermophilic conditions is possible (in about 10–20 days), as it always contains about 10% of thermophilic microorganisms [1]. Thermophilic digestion processes offer a number of advantages. The rapid metabolic activity in a thermophilic digester helps in reducing the retention time and increasing the loading rates and hence a small digester volume [4]. In addition to increased rates of methane production, which is reported to be 1.5 times faster than mesophilic digestion, thermophilic digestion has improved dewaterability and enhanced, if not complete, killing of pathogenic organisms [39]. However, changes in the overall process efficiency due to increased metabolic activity are balanced by a corresponding increase in the rates of microbial inactivation [40]. Hence, the optimal process temperature represents the best compromise between these two factors. The required optimal digestion temperature may also depend on the waste being treated. For example, higher conversion of protein is observed at 30–50 °C and conversely lower temperatures were found suitable for lipid digestion [41]. Low temperature waste digestion is slower than mesophilic and thermophilic digestion.

## pH

A pH value between 6.5 and 7.7 has been found to be optimum for hydrogen-utilizing bacterium, *Methanobacterium ruminantium*, seen in digesters and rumen [42]. Ghosh and Klass used a pH of 7.2 for optimum running of the methanogenic stage of a two-stage laboratory digester and Cohen *et al.* used 7.8 for the same [43, 44]. Maintenance of near neutral pH is due to the conversion of acid end-product to methane by the combined effect of acetogenic and methanogenic bacteria. It should be recalled that the methanogenic process is alkalizing. The major controlling buffer in this pH range is the carbonate-bicarbonate system. VFAs and ammonia also have been known to regulate the buffering capacity of the digester [45].

The sensitivity of anaerobic digestion to pH levels has been due to the critically pH-sensitive methanogenic population. However, it is evident that acid-tolerant methanogens do exist in peat bog environment [46]. Methanogenesis beyond the range of 6.5–8.0 pH has been found to be less yielding [1].

## Substrate composition

The biomass substrate used in methanogenesis is comprised of various carbon sources such as cellulose, pectin, hemicellulose, protein, lipid, starch, lignin, and other organic material at varied concentration. For a pure substrate, it is possible to calculate the amount of gas, which may be produced on the basis of a simple carbon balance. Theoretical yields of biogas ($m^3$/kg VS destroyed) from various components of organic matter are 0.886 (carbohydrates), 1.535 (fat), and 0.587 (proteins) with a methane content of 50, 70, and 84% respectively [47].

## C:N ratio

Extra attention has to be paid to the nitrogen content of the substrate biomass for two reasons. On the one hand, nitrogen is required for cell growth, a phenomenon necessarily linked to methane production; on the other, the nitrogenous compounds contribute to the buffering of the digesting liquor by the release of ammonium cation. Investigations by various authors have shown that C:N ratio of 16–19 is required for maximum methanogenic performance. Stevens and Brune used glucose and urea to adjust the C:N ratio of swine manure between 20 and 25 [48]. They have reported low methane yields at low C:N ratios because of ammonia inhibition. A concentration above 3000 mg/l of ammonia nitrogen is supposed to be toxic at all pH levels. Maximum methane yields have been reported at C:N ratios of between 16 and 19 [49]. Decreasing methane yields have also been reported when the C:N ratio increased above 20, probably because of low nitrogen availability. The findings of Hashimoto have also endorsed the above result while studying anaerobic digestion of cattle manure and molasses [50].

## Micronutrients

The bacteria in the anaerobic digestion process also require phosphorous (P) and metal ions for optimum growth. Murray and Berg have reported that nickel and cobalt ions are necessary at concentrations of 100 nM and 50 nM, respectively [51]. Molybdenum ions at a concentration of 50 nM may enhance the joint effect of nickel and cobolt. Iron cations up to 2 nM and copper ions at a concentration of 4 nM are necessary to enhance the performance of acetíclastic methanogenic archaebacteria. An increase of up to three-fold can be achieved by incorporating the above minerals to a digester deficient in these components [1, 52]. The requirement of P has also been studied and a C:P ratio of 100–200 is said to be optimum. The required optimum C:N:P ratio for enhanced yield of methane was found to be 100.2.5:0.5 [53].

## Toxins and inhibitors

It has been observed that metal ions exert a toxic effect when they exceed the required concentration. Mosey and Hughes proposed the critical value of pS > 14.0 as threshold value indicating the inhibitory presence of heavy metal ions such as $Zn^{2+}$, $Cd^{2+}$, $Fe^{2+}$ or $Cu^{+}$ and $Cu^{2+}$ [54]. Hayes and Theis described the concentrations inhibitory to anaerobic digestion [55]. Accumulation of $NH_4^+$, $SO_2$, $HSO_3^-$, and $SO_3^{2-}$ was reported to inhibit a methanogenic bacterial community at a concentration beyond 1 mg/l of digesting liquor [1]. The presence of organic compounds [amino derivatives, higher alcohols (5–12 carbon), and ketones (5–8 carbon)] is inhibitory only when their concentration exceeds their solubilities in water. Petrochemicals are toxic when they are present as derivatives of $-Cl$, $-NH_2$, $-C=O$, di–COOH, though accumulation is possible with severely increased time requirements. However, chloroform ($CHCl_3$), an analogue of methane, is a very potent inhibitor of the methanogenic archaebacteria.

## Intermediates

The VFAs form the intermediates of the anaerobic digestion process. The $C_2$–$C_5$ acids such as acetate, propionate, and butyrate may be inhibitory to methanogenesis at higher levels though they are also the substrates for the reaction. However, acetic or butyric acid inhibition is not significant. It has been observed that a concentration of 10 000 mg/l of acetic and butyric acid had no inhibitory effect on *M. formicicum* [56]. However, Andrews observed that propionic acid was inhibitory to laboratory digestion at concentrations as low as 100 mg/l and can also inhibit growth of *M. formicicum*. The composition of VFA in cattle manure biogas digester is about 87–88% of branched-chain fatty acids comprising isobutyrate, isovalarate, and were found to produce an inhibitory effect. Isobutyric acid, in particular, was inhibitory at concentrations as low as 50 ppm [57]. The toxic effect of VFAs at high concentrations is attributed either to the toxicity of the VFAs themselves or to the decrease in pH brought about by them. However, inhibition due to VFAs in anaerobic digestion is varied.

## Hydraulic retention time

Hydraulic retention time (HRT) expresses the volume of fluids in the reactor per volume of fluid passing into and out of the reactor on a daily basis. It indicates the contact time allowed between the substrate and microorganisms in the system. Maintaining optimum retention time is an important factor to cause efficient conversion of organic matter to methane. Use of very long retention times would result in inefficient use of digester capacity as it may allow the bacterial population to proceed beyond the phase of exponential multiplication. At too short HRT, the rate of bacterial multiplication may not be sufficient to compensate for the bacteria discharged into the effluent from the digester resulting in an unstable bacterial population [58–60]. The HRT maintained in conventional anaerobic digesters utilizing raw sewage solids and organic refuse ranges from 15 to 30 days [61–66]. For cellulosic material, an HRT of 10 days was reported as optimum and the lignaceous material was non-degradable even at 30 days HRT [66].

### Loading rate

The loading rate is the amount of raw material introduced into the digester per unit time. It concerns the interaction between substrate and microorganisms and directly influences the equilibrium between different physiological groups of bacteria involved in the process. With certain substances, adverse effects of overloading are immediate and drastic (for example, sewage sludge), and the effects are less drastic when the substrate is heterogeneous in nature (for example, organic refuse) [67]. High loading brings about unfavourable pH, leading to low methane production. An appropriate loading rate is required to maintain the balanced activity of different physiological groups leading to a stable digestion process. The loading rate of organic matter is expressed in terms of kilogram (kg) of volatile solids (VS) per cubic meter of digester or percentage of VS. The reported loading rate for various substrates ranges from 0.6 to 1.6 kg VS/m$^3$ for sewage sludge [63], 1.27–4.80 kg VS/m$^3$ for organic refuse [62–66], 2.56–3.50 kg VS/m$^3$ for piggery waste [68], 1.12–27.24 kg VS/m$^3$ for cattle manure [69], 2.88 kg VS/m$^3$ for manure [70], and 3.50–4.25 kg VS/m$^3$ for fruit and vegetable waste [71].

## REACTOR DESIGN

The commercial methane-generating continuous fermenters use systems, which have arrangements for retaining biomass within the reactor, and usually, the contents are not completely homogeneous. Two distinct approaches have been followed to retain the biomass. In one approach, bacterial population, which is flocculent in nature is used so that its loss during high feeding rates could be minimized. In the second approach, microbial flora, critical to the treatment process, are immobilized on different types of granular material so that the loss of biomass is restricted to the maximum possible extent. The different types of modern-day approaches to the reactor models are described below.

## Upflow anaerobic sludge blanket or upflow anaerobic sludge bed

Upflow anaerobic sludge blankets (UASBs) are very widely employed in anaerobic waste water treatments in breweries and sugar industries. The unique feature of the reactor is that it allows the flocculation of active microbial cells within the system and the size of the microbial flocculent particles is enough to sediment at a very fast rate. The sedimentation potential is very good; as such the effluent is not allowed to flow through the reactor without disturbing the sedimented microbes. The cell-biomass, therefore, is not lost through the reactor exit along with the treated effluent. The organic matter content is reduced to a greater extent. The present UASB reactors are the result of extensive work carried out by Lettinga and other Dutch scientists in the last decade [72–76]. UASB avoids plugging by reducing the volume of the packing material and uses a gas collector to encourage settling of sludge. High microbial populations are needed in addition to proper development of a granular sludge to promote settling. It has been shown that for wastes with an organic matter concentration of the order of 5000 mg/l, most of which are in solution, the utilization is of the order of approximately 90% with an HRT of less than one day, which is an extraordinarily efficient performance. But this requires careful adoption of the system. These results, of course, do show a small degree of fluctuation, and more knowledge of the physiology and biochemistry of the performance of the microbial populations involved is required.

A key factor in the system is the ability to maintain suitable sedimentation in the floc. Establishing an upflow sludge blanket system depends on suitable microbial population. For this purpose, sewage sludge is a very good source, provided the selection leading to the loss of non-flocculent material and the retention of particles efficiently is established.

The characteristics of suitable sludge blanket bed methanogenesis, as described by Lettinga *et al.*, are mentioned below [76].

- It should contain good amounts of suitable sludge that sediments well and gives a sludge bed with a concentration of total solids of 100–150 g/l.
- The flocculent occupies the upper part of the blanket. Its upward movement and penetration, to some degree, into the precise arrangement of particles within the reactor are not constant enough for the production and evolution of gas, which serves to mix the contents to some extent. This is needed to prevent more compact sediment which in turn will reduce the contact of the effluent with the microbial blanket on the bed.
- Extreme agitation should not be done as this would disturb the microbial blanket and result in the loss of biomass.

The success of UASB reactor depends on the design of the separating system through which the treated effluent leaves the digester. Inevitably some biomass leaves the digester when it reaches the turbulent area. Here, retention of biomass is essential.

## Anaerobic contact processor or anaerobic contact reactor

Anaerobic contact reactor is different from the UASB reactor in that it does not require sedimentation of biomass within the primary vessel. However, it must be capable of removing the biomass from the bioreactor in some way. Collection by sedimentation is the most economic way since one requires an associative population which may not be large enough to facilitate increased concentration of biomass in the digester but must be rapid enough to leave suspension when the effluent reaches a separating device. The reactor, in fact, uses sludge, which sediments to the bottom and contacts the raw waste. Thus, the settling ability and the mixing of sludge with the waste are important for efficient bioconversion. This type of bioreactor works well for particulate wastes, which settle easily and are completely biodegradable.

Though this process is attractive, difficulties such as the failure of organisms leaving the reactor to sediment properly in the separator have been experienced [77]. In such cases, the biomass may be collected by centrifuge and returned. However, this is relatively costlier and shear forces may damage the organisms so that activity is reduced. Flocculation or floatation chemicals may be used to facilitate the collection of biomass, although it would be necessary to ensure that they are free from toxicity. The anaerobic contact process may be regarded as a method for overcoming inadequacies in the natural retraction of microbes within the fermenter, and would not be the method of choice if a natural sedimentation could be guaranteed.

## Anaerobic attached film reactor or downflow stationary fixed film reactor

This reactor can accommodate a wide variety of wastes. Both the UASB and anaerobic contact processes exploit the ability of microbes to attach to others, yielding sedimented particles in the digester. The particulate material may in turn attach to the microbial cells so as to increase the size and effective density of the floc. Better degradation/breakdown of the substrates is thus facilitated. The downflow stationary fixed film reactor is an alternative to the above systems. Here, the approach is to deliberately attach the cells to solid support, which will invariably remain within the reactor because of its density, together with its microbial load. The solid may be static or mobile as in fluidized bed systems.

### *Static system or anaerobic filter reactor*

In static systems, the population of microbes is allowed to attach to large-sized supports. They may be rock, stone, pumice or bamboo cuttings. This retains suspended bacteria and waste in a packing material or solid support, where degradation occurs. This is advantageous to treat dilute soluble wastes. However, it is easily plugged by suspended particulate waste. These systems were first described by Young and McCarthy [78]. This system could be operated not only as an upflow device but also as a horizontal system or down-flow system [79–83]. The passage of the effluent leads to methane generation. The suspended solids are retarded in their flow and retained by allowing increased time for their breakdown. The applicability of this system to wastes with a BOD of 1000–2000 mg/l was also studied.

### *Expanded or fluidized bed reactors*

Reactors of this type have been a recent addition to the already existing bioreactors [84]. Jewell *et al.* have stated that the potential of this system could be used to the fullest only in anaerobic systems [85]. According to them, these reactors could be exploited very efficiently for dilute as well as concentrated wastes. The concentration of biomass in the reactor can approach 30 kg/m$^3$ while the bulk density of the film is in excess of 100 kg VS/m$^3$. This high density allows an 80% reduction in COD (from an initial value of 200 mg/l) from settled sewage in treatment times of no more than one hour. Additionally, the unit removes suspended solids with high efficiency from the waste stream. The expanded bed systems are resistant to shock-loading and are able to operate at ambient temperatures even when these fall close to zero.

## TWO-PHASE ANAEROBIC DIGESTION

Considering the diverse nature of the requirement of trophic microbial population in anaerobic digestion, the interspecies electron flow and the apparent limitation of methanogenic process have led to the proposal of phase separation. In phase 1, organic matter is hydrolyzed and acidified, and in phase 2 the same is subjected to methanation. It would be advantageous as the process of methanogenesis is step-wise [2, 86–88]. The environmental and operational parameters may be optimized separately to improve the overall kinetics of the process. This would not only protect the limiting microbial population from inhibitory effects of intermediates but also enhance the overall performance of anaerobic digestion.

The process is separated into acid and methane forming phases generally by selective inhibition of methanogens in the first phase digestion either by manipulation of operating parameters or by addition of some chemical inhibitors. The first phase product (acidified substrate) is then transferred to methanogenic phase either by selective diffusion or by manipulation of the flow rate [86]. Two-phase anaerobic digestion has been demonstrated for liquid and particulate substrate by many scientists [86, 88–90]. Phase separation has certainly proved better as it can handle very high loading rates in half the residence time required in conventional digestion system.

A comparison of the two-phase and conventional anaerobic digestion of soft drink waste water has indicated that in two-phase system, loading rate could be increased up to 4.8 kg VS/m$^3$/day, while the high rate system could sustain only 0.64 kg/m$^3$/day. The rate of gas production has also increased to 2.74 volumes compared to 0.4 volumes per liquid volume per day obtained in conventional biomethanation. Two-phase system has also recorded 96% of COD removal whereas it was 84% in conventional system [86]. Similar observations have been made by Rintala and Ahring, and Aoki and Kawase [88, 89].

## Substrates for methanogenesis

Recently, due to widespread use of anaerobic digestion for waste treatment as well as for biogas production, a wide variety of substrates have been tried and commercially exploited. The range of biomass materials that can be broken down by anaerobic digestion is very broad. More than 30 types of wastes with potential for methane generation have been listed in Table 2 [91, 92]. Domestic wastes like cattle manure, sewage sludge, domestic garbage, night soil, agricultural and

**TABLE 2.** Potential organic matter for methane generation

| | |
|---|---|
| Crop wastes | Sugarcane trash, weeds, corn and related crop stubble, straw, spoiled fodder |
| Wastes of animal origin | Cattle shed wastes (dung, urine, litter), poultry litter, sheep and goat droppings, slaughter house wastes (blood and meat), fishery, leather, wool wastes |
| Wastes of human origin | Faeces, urine, refuse |
| By-products and wastes from agriculture-based industries | Oil cakes, bagasse, rice bran, tobacco wastes and seeds, wastes from fruit and vegetable processing, press-mud from sugar factories, tea wastes, cotton dust from textile factories |
| Forest litter | Twigs, bark, branches, leaves |
| Waste from aquatic plant | Marine algae, sea weeds, water hyacinths |

**Table 3.** Potential biogas production from various substrates

| Substrate | Operation | | | Biogas | |
|---|---|---|---|---|---|
| | HRT (days) | LR (%TS) | Temperature (°C) | Yield ($m^3$/kg VS added) | Methane (%) |
| Sewage sludge | 25 | 6.0 | 35 | 0.52 | 68 |
| Domestic garbage | 30 | 5.0 | 35 | 0.47 | — |
| Piggery waste | 20 | 6.5 | 35 | 0.43 | 69 |
| Poultry waste | 15 | 6.0 | — | 0.50 | 69 |
| Cattle waste | 30 | 10.0 | 35 | 0.30 | 58 |
| Canteen waste | 20 | 10.0 | 30 | 0.60 | 50 |
| Barmuda grass | 12 | 1.6 | 35 | 0.22 | 56 |
| Food market waste | 20 | 4.0 | 35 | 0.75 | 62 |
| Cassava peel | — | 3.6* | 37 | 0.63 | 57 |
| Distillery waste | 10 | 3.0* | 37 | 0.76 | 56 |

*kg VS/$m^3$ day.

*Source.* Deepak Somayaji. 1992. *Microbiological Studies on Biomethanation of Mango Peel with Special Reference to Methanogens.* Ph. D. Thesis, University of Gulbarga.

industrial wastes such as piggery, poultry, crop residues, and distillery waste have been successfully used for biomethanation in the past [37]. Till recently, biogas substrates were those which were either natural habitat for the bacteria involved in anaerobic digestion (namely, cattle manure, sewage sludge, and fuel wastes) or those which were capable of supporting anaerobic digestion on their own as they contained all the necessary nutrient components. Table 3 summarizes the application of many such substrates for methane generation at different operating conditions.

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GAS

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ANALYSERS

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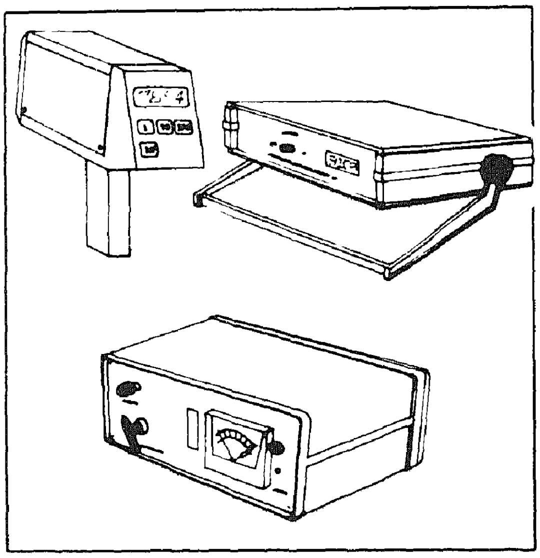

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- Air Separation
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- Hospitals/Medicine
- Biotechnology
- Bulb Industry

Usage:

- Oxygen
- Hydrogen
- Moisture
- CO, $SO_2$, NOX, $H_2S$
- Carbon Dioxide
- Gas Mixtures

GAS

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CHROMATOGRAPHS

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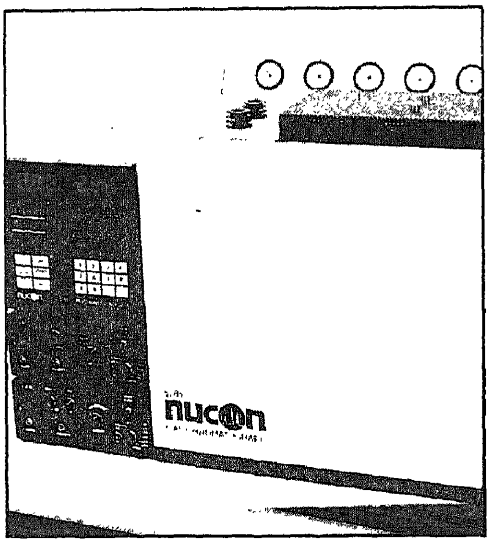

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# 7

# Improvements in microbial compost technology: a special reference to microbiology of composting

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## INTRODUCTION

Composting is the process of converting organic residues of plant and animal origin into manure, rich in humus and plant nutrients. It is largely a microbiological process based upon the activities of a host of bacteria, actinomycetes, and fungi. All kinds of organic residues amenable to the enzymatic activities of the microorganisms can be converted into compost by providing optimum conditions for biodegradation. Unless strictly controlled, composting employs the activities of both aerobic and anaerobic microorganisms.

Effective harnessing of the great biochemical activities of microorganisms for bioconversion processes has become more imperative today as modern societies are generating huge quantities of wastes. Unless these wastes are prudently managed and recycled, not only will the dwindling resources become further scarce, but environmental quality will also deteriorate to an intolerable level. In this background, conversion of organic wastes into value-added products through microbial technologies appears to be an extremely useful approach.

Recycling of organic residues through composting is an age-old practice. Yet, tremendous renewed interest has been shown in this process of late. In developed countries, practicable technologies have now been worked out for the composting of troublesome wastes such as sewage sludge [1]. Rapid composting processes based upon specific engineering designs have been proposed [2]. Even patented composting methods and apparatuses have been designed [3]. In developing countries, investigators have been engaged in improving conventional technologies of rural composting by certain mineral and microbial inputs [4, 5, 6]. Widespread interest is being shown in evaluating the role of earthworms in composting [7, 8]. Furthermore, some commercially available microbial starters have been found to be useful in the composting of industrial wastes [9]. In view of these noticeable developments in composting methodologies, it is pertinent to make an appraisal of the existing status of the technology of composting with particular emphasis on the microbiological aspects of the process.

## METHODS OF COMPOSTING

Basically, any system or design that ensures efficient decomposition of organic matter can constitute a composting method. However, some methods, worked out long ago, have been in vogue over the past several years with a little or no modifications. These methods are based upon simple manipulations of the raw materials and conditions of composting, and are being followed in most practical situations. Conventionally, two methods of composting are known in India. A brief description of these methods is given below.

### Indore method

This method was worked out by Sir Albert Howard, a British agronomist in India, at Indore in Madhya Pradesh during 1924–30. Basically, it was a systematization of the traditional composting practices being followed in China and India for centuries [10]. The Indore method is an aerobic process and hence precludes adequate supply of oxygen during the decomposition process. Waste organic materials such as straw, garbage, leaves, and plant clippings are laid in a heap or pit in alternate layers with animal manure and soil. Accordingly, a 15 cm thick and 1.5–12.0 m wide layer of organic materials to be composted is placed on a hard upland place. This is followed by a 4–5 cm layer of animal manure (dung), which is in turn covered by a sprinkling of surface soil mixed with a small quantity of lime or wood ashes, about 30 mm in all. The layers are repeated until the heap reaches a height of 1.5–2.0 m. The final layer should be of the compostable material covered by a thin layer of soil, about 60 mm. To provide optimum moisture (60–70%), water is sprinkled over each layer. The same procedure is followed if composting is carried out in pits of about 1 m deep, 1.5–2.0 m wide, and of suitable length. The heap is turned thoroughly at intervals of 3, 6, and 12 weeks. The finished compost is ready in about three months if the materials are properly shredded and layered. Generally, it takes about four months for the compost to be ready. The Indore method has the disadvantage that it demands considerable labour in construction of the heap, turning of material, and maintenance of adequate moisture. Loss of nitrogen as ammonia gas also takes place, which can be considerably reduced. Economy in use of water is also possible if composting is carried out in pits instead of heaps.

## Bangalore method

This method was worked out, firstly to overcome some of the disadvantages of the Indore method, and secondly to process night soil and city refuse. In fact, before the method was developed, the disposal of night soil collected from dry latrines in Indian towns was a real problem. Although it was known as an anaerobic method, in reality, it is aerobic to start with, followed by anaerobic decomposition later. This method is also known as hot fermentation method, as heat loss during decomposition is considerably reduced [11, 12]. Though initially worked out for towns, it can be used for compost-making from conveniently available organic materials. Under rural conditions, animal dung can be used to substitute night soil, for night soil is generally not collected in rural areas.

To carry out composting by the Bangalore method, trenches of about 1 m depth, 1.5–2.5 m width, and of any length are made at an appropriate place, generally on the outskirts of the city. If material is limited, one can go in for pits of 1 m depth, 1.5 m width, and 3–4 m length. The compostable refuse is dumped into the trench or pit and spread out with rakes or forked shovels to make a layer of about 1.5 cm thickness. Night soil or dung is then placed over the refuse in a layer of about 5 cm. The process is repeated until the trench or pit is filled up to about 30 cm above the ground level and a final layer of compostable material is placed on the top. At each layering, water is sprinkled over the material to make it optimally moist. The above-ground material is made into a dome shape and covered with about 2.5 cm mud-plaster. If all operations are properly carried out, the compost is ready in about five to six months, a period of about one-and-a-half times longer than that for aerobic composting by the Indore method.

## Modifications

Modifications of the original methods of composting have been attempted at one place or the other, from time to time, in order to speed up the process. It should be remembered that rapid composting conserves more nutrients of the compost materials than slow composting carried out at leisure. The Chinese high temperature composting method is a combination of the aerobic and anaerobic methods [13]. To make the so-called high temperature compost, after the heap is erected, hollow bamboo pipes are inserted into it both vertically and horizontally. In two to three days, the temperature of the heap rises to 60–70 °C. The poles are then removed and the heap is plastered with mud. The plaster is broken after 15 days and the heap is turned thoroughly. If need be, moisture is adjusted to appropriate levels. The heap is replastered and left for natural decomposition. The compost will be ready in about two months, whereas it takes about four months by the ordinary aerobic method.

Some quicker aerobic composting methods have been suggested [14]. Quick intermittent turning of the material is the cardinal point of these methods. These are modifications of the Indore method. With the provision of adequate moisture, the compost heap is turned thoroughly at three-day intervals. This way, a fairly good compost is ready for use in about three weeks.

## FACTORS CONTROLLING MICROBIOLOGICAL DECOMPOSITION

Present methods of composting are mainly of aerobic nature. Therefore, to understand the principles and practice of composting, one must have an insight into the physical conditions necessary for successful composting. The success in preparing good quality compost depends upon the creation of a favourable environment for the growth and activities of the microorganisms in the system. A compost heap is a miniature ecosystem where interactions between biological and abiological factors bring about the desired changes.

### Chemical nature of raw material

The main constituents of plant residues are the carbonaceous compounds such as cellulose, hemicellulose, and lignin, occurring in that order of abundance (Table 1). Nitrogenous constituents (proteins) occur to a lesser extent. Protein constituents, cellulose, and hemicellulose decompose easily. Lignin, being a complex aromatic polymer, is resistant to microbial attack to a considerable extent. That is how most components of lignin reach the finally produced humus in the compost. It is for this reason that most microflora, which develop

**Table 1.** Chemical composition of some plant materials (% of dry matter)

| Material | Cellulose | Hemicellulose | Lignin | Protein |
|---|---|---|---|---|
| Rice straw | 35.8 | 22.9 | 11.6 | 03.1 |
| Wheat straw | 37.8 | 26.9 | 18.8 | 02.4 |
| Oat straw | 36.4 | 26.6 | 18.0 | 02.7 |
| Barley straw | 40.4 | 25.3 | 17.8 | 03.6 |
| Saw-dust | 53.6 | 09.3 | 28.2 | 01.8 |
| Peanut shells | 16.8 | 42.2 | 15.7 | 14.8 |
| Cattle-dung | 28.6 | 26.0 | 17.7 | 08.3 |
| Sheep-dung | 18.7 | 18.5 | 20.7 | 22.5 |

*Source*. Derived from various sources.

on naturally decomposing plant materials, are largely cellulolytic bacteria and fungi [15, 16, 17]. Substantial cellulase activity by such fungi on waste organic substrates has been reported by several investigators [18, 19]. Hence, good raw material for composting should be predominantly of cellulosic nature. The inclusion of weeds, clippings of green grass, bushes, and green leguminous plants, which have high weeds, cellulose and low lignin contents, helps greatly in the rapid composting of mature organic residues. At the same time, lignin is not entirely recalcitrant to microbial decomposition. It also suffers slow degradation following the flush of cellulosic degradation. A number of fungi, particularly those belonging to the *Basidiomycetes* group, are well known for their lignin decomposing property [20]. Some bacteria and actinomycetes also possess lignolytic characteristics.

## Carbon:nitrogen ratio

The abundance of carbon and protein in organic matter, and the carbon:nitrogen (C:N) ratio play a very significant role in microbial food supply. Generally, C:N ratios ranging from 30 to 50 have been used for composting [21].

Higher ratios slow down decomposition and hence composting takes a longer time. On the other hand, ratios lower than 30 cause rapid decomposition and may result in an appreciable loss of nitrogen as ammonia. In fact, a higher C:N ratio causes greater conservation of the nitrogen originally present in the compostable material; but this can only be gained at the cost of composting time. The C:N ratio may be adjusted by incorporating materials such as leguminous hays, trimmings of green bushes, night soil or sewage sludge. Addition of inorganic nitrogen should generally be avoided, as it increases costs of composting. Addition of inorganic nitrogen does stimulate decomposition of nitrogen-poor residues. This recourse may be taken only when other means of C:N ratio adjustments are not available and the compost is required in a short time.

## Moisture

Provision of optimum moisture in the substrate material is essential for the metabolism of microorganisms. Moisture content of 60–70% is generally considered optimum to start with. At later stages of decomposition, it may be 50–60%. Excess moisture creates anaerobic conditions in the heap and brings about putrefaction. Putrefaction, the decomposition by anaerobic microorganisms, produces disagreeable odours and undesirable products. If the material has insufficient water, the growth and proliferation of microorganisms as well as the rate of decomposition of the organic material are slowed down or even stopped.

It is important, therefore, to ensure adequate moisture in each layer of the compost heap.

## Aeration

Aeration controls the internal environment of the compost heaps, which in turn regulates the microbiological activity during composting. Excessive watering, use of large quantities of fine and green materials for composting, and heaps of large dimensions, all these contribute to aeration. If aeration is poor, anaerobic conditions predominate. As a result, the rate of decomposition is slow. The nitrates formed during composting are converted to gaseous form of nitrogen. These escape into the air, lowering the mineral value of the compost. In all traditional methods, good aeration is achieved by giving frequent turnings to the material, as in the case of the Indore method. There is a slight loss of heat during turning, but the temperature again rises to its original level in two to three days.

While initiating layering of materials in the heap, it is useful to put a lattice of tree branches on the ground as a longitudinal axis. This will permit a free longitudinal flow of atmospheric air through the heap. The *high temperature compost* process, practised in China, uses the poles to provide adequate aeration to the heap [13]. The Beltsville Aerated Pile method, developed in USA for composting sewage sludge, is based upon forced aeration provided to the composting sludge through a loop of pipes built around the base of the sludge pile [1]. In fact, in all improved designs of composting, which have come up in recent years, good aeration has been the prime factor of innovation.

## Temperature

Under optimum conditions of air, temperature, and food balance, there is a rapid rise in temperature of the heap or pit as the decomposition proceeds. This is because of the metabolic activity of microbes present in it. In the aerobic system, the temperature rises to 50–60 °C in just a few days and goes even up to 70 °C in two to three weeks. The high temperature rise in the compost heap destroys weed seeds, pathogenic microorganisms, maggots and worms, and prevents fly breeding. When the compost is prepared in pits or trenches, the rise in temperature will not be as high as in heaps, but the rise is maintained over a longer period.

The considerable rise in temperature during the early stages of decomposition is supported by several experimental evidence. While composting palm press fibre with poultry litter, Thambirajah and Kuthubutheen observed a temperature rise to 60–70 °C in the heaps in the first three weeks, but it stabilized at 30–40 °C in eight weeks [22]. Similarly, Cordon and Waksman found maximum decomposition of horse manure at 65 °C at the initial stage, but later on decomposition was more rapid at 50 °C than at 65 °C [23]. The process of decomposition was found to stabilize at about 30 °C.

### Reaction

Reaction or pH is the least significant factor in general composting processes. The optimum pH for most microorganisms is between 6.5 and 7.5. The pH of the waste materials usually available for composting under rural conditions falls in this narrow range. Hence, the problem of pH control does not arise. No doubt, organic acids are produced during decomposition of the organic matter, yet in an active composting system, their existence is only transitory. Problems may arise if the material obtained for composting has undergone putrefaction, as appreciable amounts of troublesome organic acids are produced during anaerobic decomposition. In such a situation, addition of materials like lime or wood ash helps in neutralizing excessive acidity. However, a rise in pH beyond 7.5 may make the environment alkaline, which may cause loss of nitrogen as ammonia. A slightly unfavourable situation may be faced in the composting of city garbage, either alone or in combination with sewage sludge as the pH of this heterogeneous mixture may be lower or higher than the optimum. Addition of lime, rock phosphate, or gypsum may, therefore, prove useful in the composting of city refuse and sludge. It has been found that the mechanically produced garbage compost at Bangalore had pH value as high as 8.4. It could not be rectified to desired levels even by the addition of rock phosphate. Hence, efforts to establish inocula of the nitrogen-fixing bacterium *Azotobacter chroococcum* and the phosphate-dissolving mesophilic fungus *Aspergillus awamori* in the compost did not succeed [24]. Addition of inorganic nitrogen for raising the nitrogen content of the compost also did not succeed because of loss of the added nitrogen as ammonia. On the other hand, pH of the mechanical compost produced at Pune was only slightly alkaline and the compost could be improved with the addition of rock phosphate and inoculation with *Azotobacter chroococcum* and *Aspergillus awamori* [25]. These studies illustrate the potential pH variability that may occur in city waste materials used for composting.

## MICROBIAL PATTERNS IN COMPOSTING SYSTEMS

The occurrence and successions of microorganisms in composting systems have been examined only casually. This is understandable because qualitative and quantitative estimates of microflora are not as significant in composting as in the integrated microbiological activity. Compostable organic materials are naturally inhabited by large numbers of heterotrophic microorganisms, which bring about satisfactory decomposition under appropriate environmental conditions. Maximum increase in microbial numbers is noticed in the first one or two weeks of incubation. This is in correspondence with maximum carbon dioxide evolution during the same period [26, 16].

## Occurrence of microorganisms

In most situations involving decomposition of plant residue, fungi and some bacteria are the first invaders [27]. Although bacteria are in greater abundance than fungi in soil, in studies on the natural decomposition of organic materials, fungal flora has received greater attention. Being efficient consumers of carbon and a proportionate amount of nitrogen, fungi build up much higher biomass than other microorganisms. Burges stated that when fungi were grown on relatively simple substrates, about 40% of the substrate was converted into fungal material, 5–10% was released into the medium either as partial breakdown products or more complex materials, and the remainder was released as carbon dioxide [28]. It was this trait of fungi that enabled investigators to isolate numerous species of the organisms from naturally decomposing plant materials, and subsequently test these organisms for their biodegradation activity on specific organic residues [26, 29, 30]. The most commonly observed species of cellulolytic fungi in composting materials are *Aspergillus, Penicillium, Rhizopus, Fusarium, Chaetomonium, Trichoderma, Alternaria, Cladiosporium,* etc. Some workers have found species of *Paecilomyces* and *Sporotrichum* as efficient degraders of lignocellulosic wastes [31, 32]. Kainsa *et al.* reported an active cellulase system in *Paecilomyces fusisporus* [33]. Sidhu and Sandhu found marked cellulolytic activity in seven fungi isolated from actively decomposing sugarcane bagasse [18]. *Aspergillus* sp. and *Trichoderma viridae* were found to produce appreciable amounts of cellulase on apple pomace [19]. In fact, cellulolytic activity has been noticed in several species of fungi and bacteria isolated from soil [17]. Among bacteria that occur commonly in aerobically decomposing compost are species of *Bacillus, Cellulomonas, Cytophaga, Micrococcus, Vibrio, Pseudomonas,* etc. Nitrogen-fixing species of *Azotobacter, Azomonas,* and *Clostridium* also occur in compost heaps or pits, provided specific conditions required by them are available. Clostridia occur substantially in anaerobic conditions. Wani and Shinde isolated a number of bacteria from soil and used them to degrade wheat straw [16]. Many of them were efficient decomposers, while others evolved a limited amount of carbon dioxide from the material. The actinomycetes that occur most frequently are *Micromonospora, Streptomyces, Nocardia, Thermoactinomyces,* etc. Actinomycetes generally show their activity at later stages of decomposition. Waksman *et al.* identified many species of these actinomycetes in compost heaps [34]. In another study, *Thermoactinomyces vulgaris* grew vigorously in a decomposing mixture of wheat straw and poultry litter at 50 °C and produced good compost [35].

The most problematic constituent of mature plant residues is lignin, which largely defies microbial attack. The subject of microbial degradation of lignin has been widely reviewed [20]. Despite substantial microbial recalcitrance, some fungi and a few bacteria are capable of degrading lignin gradually. The most important lignin degraders are white-rot fungi belonging to *Basidiomycetes* [36]. Species of *Polyporus, Pleurotus, Collybia, Poria, Fomes, Trametes, Sporotrichum, Cyathus,* and *Coriolus* have been commonly found to degrade lignin molecules or its biodegradation products [20]. They produce enzyme laccase or phenol oxidase or both and hence bring about the breakdown of lignin. *Pleurotus* sp. and *Cyathus stercoreus* grow well on wheat straw and bring about substantial degradation of the lignocellulose in the straw [37, 38, 39]. Rarely, lower fungi like *Aspergillus* and *Penicillium* have also been shown to decompose lignin [40]. *Pseudomonas, Bacillus, Arthrobacter, Flavobacterium,* and *Micrococcus* are bacteria that have been found to attack lignin [36]. Among actinomycetes, species of *Nocardia* are the most active lignin degraders.

## Microbial development in relation to temperature

Some early studies reveal interesting patterns of microbial development during composting, which are worth describing. While composting horse dung, Cordon and Waksman observed that the most rapid decomposition of the material takes place at 65 °C [23]. After the initial period, the process was found to be more rapid at 50 °C than at 65 °C. No organism capable of decomposing cellulose was active at 75 °C. Only some spore-forming hemicellulose-decomposing bacteria were present. At 28 °C, there was considerable delay in decomposition. However, after a lapse of about 10 days, extensive microflora developed in the system and the manure began to decompose rapidly. At this temperature, the microbial population was highly heterogeneous—consisting of bacteria, fungi, actinomycetes, and protozoa. At 65 °C, bacteria and actinomycetes were largely involved in the decomposition, while fungi appeared only rarely. But at 50 °C, some thermophilic fungi were active besides bacteria and actinomycetes. In the composting of palm press fibre with poultry litter, Thambirajah and Kuthubutheen noticed that the temperature rose to as high as 70 °C in the compost heap and varied from 30 to 70 °C in eight weeks of decomposition [22]. Throughout the period, the number of thermophilic fungi remained higher than that of mesophilic fungi. Interestingly, survival of the mesophilic bacteria was not affected by temperature changes. Their numbers remained quite high even at high temperatures. Mishra *et al.* isolated thermophilic fungus *Humicola lanuginosa* from actively decomposing compost, which showed significant degradation of wheat straw at 50 °C [41].

## MICROBIAL INOCULANTS FOR COMPOSTING

There is no doubt that good compost is the product of good microbiological activity in the heap. The necessary microorganisms to induce this activity are normally abundant in compostable materials. Isolating the microorganisms from soil and decomposing materials and introducing them to the compost environment after laboratory attenuations may hardly serve any significant purpose. On this basis and on the basis of some experimental evidence, it was concluded that the use of microbial inoculants would be unnecessary for composting [14]. Only the addition of some inorganic materials like lime and rock phosphate was considered useful. Nevertheless, there is tremendous variability in the biochemical competence of microbial strains in nature; it seems reasonable that some of them might do a better job in breaking down organic substances than others. This has been the basis of the resurgence of interest in the selection of suitable microbial strains to achieve more efficient decomposition of organic materials. Considerable interest seems to have been shown in this field over the past 15 years, particularly in Asian countries, as evident from research reports. Several fungi and some bacteria have been screened out from soil and decomposing plant residues and evaluated for their biodegradative activity, taking carbon dioxide evolution as the criterion of enhanced biodegradation [26, 16, 29, 30]. Some of the microbial isolates proved significantly better than many others in bringing about degradation of various organic residues, while most of them gave more or less an edge over uninoculated and unsterile materials. It is evident from published records that the main target of isolations was the fungi. This is mainly because at the initial stage of decomposition, fungi generally dominate over other groups of microorganisms. Such studies indicated the potential of selected organisms as inoculants for composting. Out of the results of a nationally coordinated research programme for *Microbiological Decomposition and Recycling of Organic Wastes* in India, Bhardwaj and Gaur have compiled extensive information on the isolation, selection, and use of fungal cultures for rapid composting of organic wastes [42]. Most of the organisms were mesophilic fungi, but a few thermophilic strains such as *Aspergillus fumigatus* and *Humicola lanuginosa* also proved beneficial as inoculants [41]. Out of the collection of mesophilic fungi, some of the strains, namely, *Trichurus spiralis, Paecilomyces fusisporous, Aspergillus awamori,* and a few species of *Aspergillus, Penicillium,* and *Trichoderma,* were outstanding.

*Aspergillus awamori,* which had earlier been isolated to be good phosphate-dissolving fungus, was found to show this property substantially [43, 44, 45]. *Paecilomyces fusisporus* was found to be an efficient degrader of lignocellulosic wastes on the basis of cellulase activity and humus formation [31]. Several other studies found microbial inoculation with selected fungal strains useful in the composting of various plant residues [46, 47]. Mathur *et al.* noticed significant improvement in the fertilizer value of rice straw compost with the employment of the inoculants of some selected fungi and phosphate-solubilizing organisms [48]. The straw was amended with a little inorganic nitrogen and 2% rock phosphate. Pore *et al.* found *Trichoderma* sp. as more useful for the composting of a mixture of crop residues, grass, and tree leaves than *Aspergillus* and *Paecilomyces* [49]. Inoculation with a selected species of *Trichoderma* shortened the composting time of rice straw by 20 days, but had no effect on corn stubbles and banana leaves [50]. Choi *et al.* found thermophilic actinomycetes (*Thermoactinomyces vulgaris*) as good inoculant to produce compost from a mixture of rice straw and poultry faeces [35]. The compost produced by using the inoculant had better effect on crop plants than that made from uninoculated material.

More elaborate experiments were done under coordinated research scheme on organic recycling employing inoculants of *Trichurus spiralis*, *Paecilomyces fusisporus*, and *Aspergillus* sp. [42]. Effect of inoculants was compared with the input of fresh cattle dung to the compostable materials at the rate of 8–10% on dry weight basis, which worked out to 40–50% on wet weight basis. While in most cases, microbial inoculants, singly or in combination, gave better results than the uninoculated materials, comparisons with cattle dung were almost consistent. Thus, selected microbial inoculants or cattle dung appeared to be competing alternatives. By the indications of these results, microbial inoculation could be useful under conditions where animal dung is not available; but under situations, where animal manures or other such biologically active materials are available for co-composting, special microbial inoculants may not be required. At the same time, however, the concept of microbial inoculants has led to the commercial availability of certain preparations claimed to be activators of composting. Tests conducted on their utility have often been found to be positive. For instance, Jadhav and Babar evaluated two commercial starters (activators) to compost sugarcane bagasse and pressmud, mixed in various proportions, and found that they accelerated biodegradation of the material almost equally [9]. Similarly, it was reported that such an activator named B-2 was being used for composting in Thailand [13]. As pointed out by Rodale, such activators appeared in USA in the 1940s and early 1950s, but when verified by properly conducted experiments, the materials did not prove to be of their publicized worth [14].

Compost enriched with some other inputs, additional to the inoculants of fungal cultures used to enhance decomposition, has also been evaluated for its quality and manurial effects on crop plants. The set of inputs used to make the so-called *enriched* compost consists of the cultures of certain fungi, phosphate-solubilizing fungi or bacteria and nitrogen-fixing *Azotobacter chroococcum*, supplemented with 0.5–1.0% rock phosphate on $P_2O_5$ basis [42, 5]. On the basis that during initial period of composting temperatures rose beyond the mesophilic range, inoculation with *Azotobacter* was resorted to after two or three weeks of decomposition; however all other inoculants and rock phosphate were introduced at the start. Some inorganic nitrogen was also added to adjust the C:N ratio of the compostable material between 50 and 60. Composting was done by aerobic method in cemented pits with four intermittent turnings in a period of three to four months. Trends of the results of these experiments on enriched compost are evident from Table 2 [5]. The results showed usefulness of the aforesaid inputs in producing better compost. These trends were corroborated by many other reports [51, 48, 25]. In all these studies one or the other inoculant of fungi, phosphate-solubilizing microorganisms and *Azotobacter* was used with the addition of varying levels of rock phosphate (1–5%). The composts prepared by these inputs were found to be more effective on crop plants than the composts made without any microbial and mineral inputs [52, 53].

There seems to be a conviction in the value of microbial inoculants and rock phosphate used in producing enriched compost in the light of some other national and international reports. Darmwal and Gaur inoculated rice straw with the cultures of *Aspergillus awamori* or *Aspergillus niger* and associative nitrogen-fixer *Azospirillum lipoferum* and incorporated the straw in the soil in pots [54]. The straw so treated produced better effect than the uninoculated straw on wheat plants. Halsall and Gibson studied the growth of a number of diazotrophs (asymbiotic nitrogen-fixing bacteria) on wheat straw decomposition products such as cellobiose, glucose and xylan, and carboxymethyl cellulose, either alone or in co-culture with an efficient strain of cellulolytic bacterium *Cellulomonas* [55]. All diazotrophs including *Azotobacter, Azospirillum, Beijerinckia,* etc. utilized wheat straw decomposition products and showed nitrogenase activity, which lasted for 15–18 days. Kimura gave a patented process for the production of organic fertilizer

**TABLE 2.** Role of microbial inoculants and rock phosphate in the composting of organic wastes

| Input to composting material | Sugarcane trash | | | Plant leaves and grass | | |
|---|---|---|---|---|---|---|
| | Total N (%) | C:N ratio | Weight loss (%) | Total N (%) | C:N ratio | Weight loss (%) |
| No input | 1.25 | 26 | 53 | 1.33 | 23 | 42 |
| 1% rock phosphate (RP) | 1.36 | 23 | 57 | 1.45 | 21 | 51 |
| RP + *Azotobacter* culture (AC) | 1.40 | 23 | 56 | 1.58 | 19 | 53 |
| RP + P-solubilizing culture (PSC) | 1.35 | 21 | 54 | 1.60 | 18 | 59 |
| RP + AC + PSC | 1.51 | 18 | 61 | 1.63 | 18 | 59 |
| Original material | 0.32 | 123 | — | 0.75 | 60 | — |

from coral reef powder, animal manure, sewage sludge, and ground plant fibre with inputs of some organic and inorganic substances and cultures of microorganisms such as *Azotobacter vinelandi*, *Bacillus megaterium*, and *Trichoderma* [3]. From these findings, it appears that the enhanced biodegradation by fungal inoculants could exert associative effect on growth of diazotroph inoculants like *Azotobacter* and solubilizing effect on rock phosphate, resulting in composts richer in nitrogen, soluble phosphate, and humic substances. However, these probabilities need further verification in order to explain fully the observed role of various microbial inoculants in the process of composting.

An approach that is evident from recent publications is that composting materials were inoculated with known lignin-degrading fungi, either alone or in association with some lower fungi or certain diazotrophs. Accordingly, if lignin in the lignocellulose complex is partially degraded, the process proceeds rapidly later on. Kakezawa *et al.* achieved rapid decomposition of rice straw by providing it with inoculum of *Coriolus versicolor* [56]. Inoculation of wheat straw with *Cyathus stercoleus* and *Beijerinckia indica* increased nitrogenase activity of the nitrogen-fixing bacteria [39]. When wheat straw was inoculated with the cultures of *Pleurotus* sp. and *Azotobacter chroococcum*, nitrogen content in the decomposed straw was found to increase substantially over that obtained by the inoculation with the *Azotobacter* [37]. As observed by Bowen, mixed cultures of some lower fungi and lignin-degrading basidiomycetic fungi showed better degradation of wheat straw than individual groups of the two classes of fungi [57].

## INORGANIC ADDITIVES IN IMPROVING COMPOST QUALITY

The quality of compost has always been a major concern. With the entry of phosphatic fertilizers in Indian agriculture in early 1950s, considerable emphasis was given to the making of super-digested or super-reinforced compost. This was based upon the addition of superphosphate fertilizer to composting materials. The compost so made was found to be of much improved mineral quality [58, 59, 60]. The utility of sparingly soluble phosphates such as rock phosphate and basic slag (a by-product of steel industry) in the decomposition of various organic materials both in the soil and composting systems was investigated [61, 62]. However, due to the easy availability of phosphatic fertilizers, this work did not receive much attention subsequently. It was mostly in the 1980s that workers turned to evaluate the role of some inorganic inputs in composting. Sufficient reserves of rock phosphate as well as pyrites are available in India. Most of the Indian phosphate rock is not fit for industrial production of phosphatic fertilizers and hence could be used for compost enrichment. Rock phosphate has only negligible amount of soluble phosphorus and as such is not of much fertilizer significance.

Compost made by conventional methods is generally poor in nutrients, especially phosphorus. Hence, there is a necessity for improving the organic manure by suitable inorganic additives in suitable proportions. Mathur *et al.* composted organic materials with the addition of Mussoorie rock phosphate at rates of 5–25% and found that sufficient plant-available phosphorus was produced in the compost [4]. They also found that solubility of phosphorus in rock phosphate increased with the addition of pyrite, a mineral containing iron and sulphur. Subsequently, Mishra *et al.* produced compost with the incorporation of 25% rock phosphate in the compost materials, employing a decomposition period of 90 days in aerobically managed pits [63]. The compost was found to be appreciably rich in citric acid-soluble phosphorus. The compost was also highly rich in total phosphorus as revealed in Table 3 [63]. The most significant merit in this compost was its higher content of citric acid-soluble phosphorus, as compared to normally made compost and rock phosphate itself. At the same time, it was found to be relatively poor in nitrogen and water-soluble phosphorus. When tested on wheat crop in field trials, the compost proved its worth. The effects in terms of crop yields and uptake of phosphorus by plants revealed that the rock phosphate-enriched compost could act as a good substitute to commercially produced phosphatic fertilizers. Many later studies verified this significance of the compost and the utility of rock phosphate transformations during composting [45, 64, 65]. The compost came to be known as *Phosphocompost*. Studies conducted by Asija *et al.* revealed that rock phosphate was as effective in enriching the compost with phosphorus and nitrogen as superphosphate [59]. Since rock phosphate is a complex material containing tremendous amounts of calcium and substantial amounts of iron and sulphur, the rock material also provides these elements to

**TABLE 3.** Nutrient composition of rock phosphate-enriched compost and normal compost

| Nutrient | Normal compost | Rock phosphate-enriched compost | Rock phosphate |
|---|---|---|---|
| Total N (%) | 1.300 | 0.950 | — |
| Total P (%) | 0.204 | 3.130 | 8.40 |
| Organic P (%) | 0.054 | 0.662 | — |
| $NaHCO_3$-soluble P (mg/g) | 1.200 | 0.630 | 0.18 |
| Water-soluble P (mg/g) | 0.310 | 0.200 | — |
| Citric acid-soluble P (mg/g) | 0.519 | 15.240 | 2.20 |
| pH | 8.600 | 8.800 | 8.80 |

*Source* Mishra M M, Kapoor K K, Yadav K S. 1982. *Indian Journal of Agricultural Sciences* **52**: 674-678.

the phosphocompost. Singh and Yadav produced excellent compost by rock phosphate enrichment of rice straw and found appreciable amount of calcium oxide in the compost [66].

A few studies have also been conducted to understand the mechanism of phosphate release from insoluble rock phosphate. These studies attribute the solubilization mainly to humic acids produced during composting [64, 65, 67]. For instance, Singh and Amberger found highly increased amount of humic acid and fulvic acid in wheat straw compost made by the addition of 25% rock phosphate [67]. They also found that 80–85% soluble phosphorus/calcium was retained in humic acids, the retention being much higher in fulvic acid than in humic acid. It, thus, appears that microbiologically mediated process of humification is mainly responsible for bringing about solubilization of elements in rock phosphate during composting.

In the composting of wheat straw in small containers with a little addition of cow dung, mature compost, and soil, the author (unpublished results) observed that carbon mineralization of the composting material and numbers of bacteria and fungi, determined at different intervals, increased significantly with the addition of 5–25% of Mussoorie rock phosphate. This stimulates microbial activity in the compost, transforms the inorganic material itself and increases humification of the organic materials subjected to composting.

As phosphocompost is relatively poor in nitrogen, attempts are being made to improve the nitrogen content along with phosphorus enrichment. Paddy straw was composted with 25% rock phosphate, 10% pyrite, and 2% urea-nitrogen [68]. All added nitrogen was lost in the form of ammonia during the treatment, where only rock phosphate was added to organic matter; but sufficient quantity was conserved when pyrite was also added. Pyrite, being sulphur containing mineral, is oxidized to sulphuric acid by sulphur-oxidizing bacteria like *Thiobacillus thiooxidans*, which help in the retention of ammonia. This signified the role of pyrite as an inorganic additive to compost. Greater solubilization of rock phosphate was observed when pyrite was added during composting [4]. Yet, despite pyrite addition, loss of added nitrogen was considerable and hence it was concluded that addition of 2% nitrogen to phosphocompost might not be beneficial.

Further efforts were made to reduce the quantity of rock phosphate as well as nitrogen. Phosphocompost was produced by using 10% rock phosphate, 10% pyrite, and 1% urea-nitrogen [6]. It was observed that by lowering the addition rates of rock phosphate and nitrogen, phosphocompost, substantially rich in citric acid-soluble phosphorus and relatively rich in nitrogen could be obtained. The compost was not as rich in citric acid-soluble phosphorus as it was with the addition of 25% rock phosphate; yet it produced comparable effect on crop plants with that obtained by the enrichment of 25% rock phosphate. Thus, economy in

**TABLE 4.** Nutrient composition of nitrogen-enriched phosphocompost

| Inputs of composting material | Total N (%) | C:N ratio | Mineral N (μg/g) | Citric-soluble P (m/g) | Total P (%) |
|---|---|---|---|---|---|
| No input | 1.16 | 21.6 | 237 | 1.15 | 0.24 |
| 10% rock phosphate | 1.06 | 22.6 | 249 | 6.65 | 1.37 |
| 10% pyrite | 1.21 | 19.5 | 182 | 1.23 | 0.19 |
| 1% urea | 1.50 | 16.3 | 1444 | 1.20 | 0.33 |
| 10% rock phosphate + 1% urea N | 1.43 | 14.6 | 1491 | 7.37 | 1.50 |
| 10% rock phosphate + 10% pyrite + 10% urea N | 2.00 | 10.4 | 4526 | 7.80 | 1.29 |

*Source.* Singh S, Mishra M M, Goyal S, Kapoor K K. 1992. Preparation of nitrogen and phosphorus-enriched compost and its effect on wheat (*Triticum destivum*). *Indian Journal of Agricultural Sciences* **62**: 810–814.

the use of rock phosphate was evident without appreciable loss in the fertilizer value of compost. The data on the mineral quality of the compost are presented in Table 4 [6]. The compost made by the combination of pyrite and urea-nitrogen was comparable to phosphocompost in nitrogen content, but it was very poor in phosphorus.

## VERMICOMPOSTING

Involvement of earthworms in composting, in association with usual microorganisms, constitutes worm-composting or vermicomposting as it is generally called. The role of earthworms in processing organic materials and in improving soil fertility has been known for centuries. Sir Albert Howard, the originator of the organized aerobic composting method (Indore method), made many practical observations about the importance of earthworms in the breakdown of organic materials and in soil fertility maintenance [14]. There is a vast reserve of information about the activity of earthworms in natural ecosystems [69]. Nevertheless, there has been a spurt of interest in these organisms from the point of view of their appropriate utilization for the processing of organic waste materials [70, 8, 7]. Lofs-Holmin found earthworm-mediated treatment of raw sewage sludge as a practicable method [7].

It is well known that earthworms do miraculous preliminary work in homogenizing organic materials, thus creating favourable conditions for their actual decomposition by microorganisms. At the same time, wormcasts, the hallmark of earthworms' activity in soil-mixed organic materials, are reported to be rich in nutrient elements. Obviously, these casts contribute to the value of the compost. Furthermore, it is acknowledged that compost heaps containing sufficient earthworms need a little or no turning of the material. Hence, worms also serve as good ventilating system in the heap or pit.

Besides earthworms' basic capacity to macerate organic residues, it has been reported that vermicompost is richer in plant nutrients than the non-worm compost [71]. However, there are claims to the contrary too. Worm-worked composts differed from simultaneously produced wormless composts only in their early finishing and physical structure, but no significant differences were noticed in their nutrient composition [72]. Shinde *et al.* analysed vermicomposts made from processing wastes of vegetable market with the help of three different species of earthworms [73]. They also analysed samples of two vermicomposts marketed by a private organization and compared them with well-decomposed farmyard manure. No significant difference was found between the nutrient content of vermicomposts and farmyard manure. Meticulous analyses are needed to reveal the real mineral value of worm-worked compost *vis-a-vis* the compost made by usual methods. However, it appears to be certain that earthworms help in shortening the period of composting. This trait of the organisms can be made use of in the composting of various organic wastes, irrespective of rural or urban origin.

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## 8

# Vermiculturing

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## INTRODUCTION

The Industrial Revolution has destroyed the healthy relationship that mankind had with Nature earlier. For centuries, man has got rid of waste in a confused and ecologically disastrous way by burying or burning it. It did not seem appropriate for him to integrate different processes in the collection and treatment of waste in the course of numerous industrial changes that have taken place in the last century. Only recently, scientific requirements linked to the protection of our natural environment have produced a social awareness and a genuine desire to ensure natural ecological balance. The problem of waste disposal has become very acute in towns and cities in the country as disposal facilities have lagged far behind the quantity of wastes produced. The common methods used currently for garbage disposal pose serious threat to the health of the environment. We treat Nature as a self-contained physical system, a resource to be exploited, or a colourful relief from a largely artificial environment.

What is the quality of life in our cities today? Garbage lying on the streets for days is a common sight. Sometimes a municipal truck collects and heaps the garbage inefficiently, spilling it all over. The garbage is then either dumped as landfill material on the outskirts of the city or burnt, producing foul smoke and creating unhygienic conditions.

Composting the garbage by new processes to recycle all kinds of biodegradable solid wastes as well as sludge from sewage at a rate fast enough to match the rate of production of these wastes is an environment-friendly and cost-effective solution. The Institute of Natural Organic Agriculture (INORA), being aware of the demands concerning waste treatment, has developed essential methods of analysis for controlling environmental pollution and for utilizing the high quality of by-products stemming from wastes. INORA works towards controlled eco-industry by doing research in macrobiology, microbiology, and physics. It selects high performance species of earthworms such as *Eisenia foetida, Eudrilus eugenine, Perionix excavatus,* and *Drawida willisi.*

The results with these species on vermicomposting are converted from experiments to actual creations. INORA can thus offer advice on the building of appropriate treatment plants.

The eighties demonstrated this really eco-technological and sociological revolution to which INORA has contributed with the introduction of selective collection and second generation processing methods, such as the Total Earthworm Technology, supported by microbiology and biogas systems. INORA has been focusing on the eco-industry over the past decade and wants to bring it under control with the help of the expertise and financial support of approachable collaborators. It will use all the available methods right from the collection of refuse to improved treatment for producing final products, which are totally recycled without further waste production.

## INTRODUCTION TO VERMICOMPOSTING

Wastes containing organic matter like domestic waste (e.g., vegetable matter, paper, cardboard, meat, and food wastes) or agro-industrial waste can be treated biologically.

### Reduction of particle size

There are two processes.

1. *Removal of all non-organic matter.* In India, where labour cost is cheap, this can best be done manually. All non-organic matter like metal, rubber, plastic, and glass can be collected separately and sent to different factories for recycling.
2. *Size reduction of organic matter.* Organic matter, when left to decompose on the streets, creates unhygienic conditions and causes environmental problems. Once this organic waste is separated, it becomes necessary to reduce its particle size mechanically to small sizes of less than a centimetre in length and breadth. For this purpose, the organic waste has to be passed through a shredding machine, which forms the first unit of the INORA process.

In the next stage microorganisms are used to bring about a biochemical change, i.e., to reduce the carbon content in this shredded matter by the emission of carbon dioxide. There is also the biological pulverization of the matter (reducing the waste to dust size). This pulverized matter is pre-digested to organic matter having a sufficiently low carbon-to-nitrogen ratio. Many organizations stop at this process and advise farmers wrongly to use this matter as fertilizer.

INORA uses this material in their new design of a biogas plant along with cow dung or any animal dung, as well as human excreta, for further anaerobic fermentation. Bacterial species, different from the aerobic ones, further break down the organic matter, producing methane (70%), carbon dioxide (30%), and hydrogen sulphide (a small quantity). The mixture can be used as an energy source. The effluent contains solid waste and water, which can be separated and used again for irrigation, since this waste has liquid manure properties.

## Vermicomposting

The solid residue has a low carbon content. It is mixed with materials of high nitrogen content, mostly vegetation. This pretreated mixture is then fed to earthworms. The gut digestion by earthworms is the vermicomposting process carried out under strict aerobic conditions, i.e., in the presence of oxygen and certain types of microorganisms in the earthworm-gut. Certain types of earthworms ingest, digest, and excrete vermicompost with excellent nutrient contents. Ingestion ensures the sorting of only organic matter while digestion accelerates the maturing process. Excretion ensures the grading of the vermicompost as opposed to any inorganic matter, which may be existing in the waste and is not concerned with this biological activity in the earthworm's gut.

The use of earthworms for the transformation of organic matter has been known for centuries. References are found in the Sanskrit works of *Rishi* Parashar. Darwin gave some scientific basis for the use of vermicompost for agriculture. However, the author was the first in India to have suggested some techniques for large-scale industrial use of earthworms for converting all kinds of organic wastes into tonnes of compost and also its actual field utilization. Propagation of earthworm technology on a large, medium, and small household scale basis was also initiated through the establishment of the INORA as a special division of the *Know How Foundation.* There are two distinct separate products:

1. biologically graded vermicompost for use as organic biologically developed fertilizer for soil improvement; and
2. crores of earthworms produced continuously and used as a pro-biotic food for animals like cows for giving better and more milk and also in aqua-culture for better fish.

When earthworms are the primary end products, the process is called *vermiculture,* and these newly produced earthworms need to be carefully cultured so that they do not contain harmful matter like heavy metals.

The basic technical aspects have taken over a decade to clear up. It was necessary for INORA to wait for adequate research funds to be raised to enable its scientists to develop a scientific and industrial approach. The early experiments in the eighties could not succeed for lack of coordinated scientific, industrial, economic, and socio-cultural approach to the problem. In this context, it may be stated that the method adopted by INORA is the only one well adapted to the treatment of urban, rural, and industrial waste in quantities up to 21 tonnes/day unit. There could be several such units in a city.

Sewage sludge is another problem. INORA has done some preliminary work in this direction but would need more time to study the treatment of sewage sludge in the aerobic and anaerobic processes, followed by earthworm composting in tandem.

## Different stages and methods

The aim of INORA was to examine the feasibility of a process for developing a total picture of the plant and the nature of the component parts. For that, firstly, it questioned certain basic ideas. For example, the direct treatment of waste by earthworms turned out to be doubly negative as they do not stand up to the heat generated by fresh urban waste and demand conditions that are incompatible with the destruction of undesirable organisms like insects and weeds. The result was the concept of bisanitization and the indication of specifications of the earthworm beds in which vermicomposting on a large scale was possible.

Secondly, the whole process, i.e., picking, possible crushing, and transporting, was integrated into a single process and a study of the interactions between different physical and biological processes was carried out. INORA has also clarified that vermicomposting is possible not only on a small household scale but also on a large industrial scale. INORA, with its organization of the plant on a unit basis, has shown that there need not be any restriction on the size of the plant.

The initial phase of about three years of trials was to allow the examination of certain alternatives and the definition of very precise restrictions. By putting together all the experiences, it has come out with the INORA process, which was carried out and tested at various places in the country.

### THE INORA PROCESS

As already stated briefly, the actual use of earthworms on an industrial scale is what makes the INORA process different. Vermicomposting has been advocated since the end of the Second World War; but the suggestions were often weird. Some good attempts have also been made to make it useful only for household garbage. This has led to the belief, existing even today, that earthworm breeding is not feasible and not of much interest as people (even scientists) based their ideas on unscientific and anecdotal approaches.

After several basic experiments and questioning the unhelpful traditional approaches to earthworm breeding, the first successful plant for earthworm technology was set up on an industrial scale. Since then, the areas of use of the INORA process have been increasing. It has now set up nearly 50 large plants all over the country, although initially the process started with household waste. By and large, the INORA process has improved the techniques for decomposition of wastes from the farm produce industry or agriculture.

## The biological means

### *Selection of biological methods*

The INORA process exploits microorganisms in the best possible way for transforming the organic matter. It would also avoid the drawbacks, which may arise from the activity of these creatures, like the pathogenic effect, the loss of valuable components such as nitrogen or the production of noxious smells produced in anaerobic conditions.

### *Bisanitization or accelerated aerobiosis*

This process makes use of aerobic microorganisms during the first stage. These are germs which live in well-aerated conditions with plenty of oxygen and heat. In fact, this heat is a result of their own biological activity. Human bodies are kept at 98.6 °F by our metabolism using the organic energy in our food. Similarly, these microorganisms, by biologically burning the organic compounds using a great amount of oxygen, produce simpler molecules, $CO_2$, and heat. By ensuring high oxygenation, a rise in temperature of up to 70–75 °C in the matter as a whole is obtained. This ensures the destruction of most of the pathogenic germs, weed seeds, invertebrates, and even small mammals which travel with the collected refuse. During this processing, the heat-loving microorganisms produce antibiotics, which complete the sanitization of the substrate. Gradually, the amount of decomposable matter decreases, and the activity of these microorganisms ceases. Consequently, the temperature of the substrate is also reduced. The quality of the matter becomes pulpy; but is still insufficiently ripe for satisfactory use in agriculture.

### *The biogas plants*

Waste materials like animal dung and human excreta can be brought in now for mixing with the pulpy material in which components such as cardboard and bark are mixed in the mixing tank. The entire mixed substrate now enters the bottom of the biogas plant, which is directly connected through a vertical pipe to the biogas plant. Organic matter like water hyacinth and/or American grass can be put in the mixing tank after shredding. Such a mixture of organic matter, with the output of the bisanitization process, makes the material extremely useful for further anaerobic digestion in the biogas plant where the bacteria from the cow-dung and human excreta are available. These bacteria are of two types—acid forming and methanogenic. These operate most efficiently at a temperature of about 35 °C, which can be maintained easily.

### *The earthworm*

The anaerobically treated sludge comes out of the biogas plant in a fairly good condition. This sludge is further mixed with biomass, mostly nitrogenous in nature. It is then fed to earthworms for ingestion. The aerobic and anaerobic stages help convert the organic matter into the right type for rapid consumption and digestion by the earthworms. This is done in long beds under sheds, which can control temperature and moisture and also provide aeration due to which the compost is made rapidly and the earthworms proliferate in number. When their foodstuff is in abundant supply, they produce one or two earthworms a day, which will live for 6–7 years on an average. Their population is limited by their food and these creatures come up to the surface of the bed after consuming all the organic material at the lower levels of the bed. They eagerly await the supply of fresh food being loaded at the top. If a plant receives 30 tonnes of purified substrate a day, the initial inoculum soon reaches a population of between 1000 and 2000 million, and at this level the supply of food becomes crucial. As a result of this either a stop or a slowdown in reproduction occurs. The population eventually stabilizes by replacing the individuals, which die of various causes such as physical or accidents. There is no epidemic or high mortality rate if conditions concerning temperature and humidity are provided in the bed by putting in sheds which are covered with jute cloth and watered adequately.

During the vermicomposting stage, the organic matter is digested more or less, i.e., sorted by the earthworms' intestinal activity, the only exception being large pieces of wood, which are insignificant. This digestion process creates a biological sorting which will permit the complete separation of organic matter subsequently. This ingestion–digestion process results in a very meticulous sorting. All the fragments of the smallest pieces of refuse from the smallest breadcrumbs are ingested, digested, and mixed up in the digestive tract, and finally disposed of as standard earthworm droppings. Sieving will later make separation easier. Both in domestic sorting by visual selective collection and in mechanical sorting units, the separation of the object can be done easily. The hungry earthworms in their beds do not miss even the smallest particle of tobacco or a thread. Even large pieces of card or thin wooden strips from crates initially softened up by the bisanitization process do not escape their voracious appetite. Hence the major virtue of earthworms is to allow a total separation of organic matter which, in turn, will enhance the residual matter which has been made cleaner.

The second immense faculty is that of digestion itself. It is a complex process combining the numerous enzymes produced by these creatures and by the microorganisms with which they cohabit. It leads to the production of a homogeneous organic matter which is totally ripe. With the normal composting method, at least 9–12 months are required to obtain homogeneous organic matter of comparable maturity. The earthworm will do this work after two pretreatments in 10–15 days. This enables us to carry out the process of maturation under cover and shed, in controlled conditions quite independent of the ambient climatic conditions.

## ASSESSMENT

INORA has been operating several plants in the past 5–6 years. The contents of the final compost have been measured to find out the percentages of the nutrients—nitrogen, potassium, phosphorus, microorganism counts, and the micronutrients (mostly in parts per million quantities). The richness of the compost is thus verified. In the entire process, fresh additions of organic matter occur in different stages. This enables the nutrient percentages to be controlled suitably to provide tailor-made compost for the needs of different soils.

### Environmental assessment

#### *Water*

The process as a whole uses up nearly 700 litres of water per tonne of compost produced, and this is fully recycled with no liquid effluent to contaminate rivers. Most of this water comes from fruits, vegetables, and other organic matter used in the process.

#### *Gases*

The exchange of gases is only through biological respiration, i.e., oxygen is consumed and water vapour and carbon dioxide are released. Carbon dioxide is released at a rate comparable to the natural process taking place in grasslands and forests. Hence there is no additional contribution to the greenhouse effect.

#### *Pollutants*

These can be monitored by correct proportions of earthworms. If, by chance, there are any heavy metals, the earthworms collect and store them in their bodies without altering their actions and life. These creatures are thus natural separators of heavy metal pollutants.

### *Aesthetics*

The aesthetic consideration depends on the type of industrial architecture chosen and the care taken of the surrounding area, since all the processes take place under cover. The noise pollution levels are far lower than those caused by trucks bringing in the waste and taking away the products. There is no final waste. The INORA process does what nature does but in a controlled and accelerated manner.

Besides, vermicompost helps in appreciably slowing down the exploitation of fossil carbon resources; saving the nutrient sources; and contributing to the restoration of the physical, chemical, and biological qualities of soils, especially agricultural and forest soils.

## Financial assessment

The present financial assessment leads to a running cost that depends mainly on the labour costs because a major part of the work is done manually. It is, therefore, a variable cost depending from place to place.

The other expenses come from the costs of sheds and earthworms as also the thermophilic inoculants. This comes to Rs 56 000 per shed of four beds. Each bed could produce about one tonne of compost in 15 days, the selling price of which is around Rs 2000 per tonne. In addition, there is income from the biogas plant also. There are many hidden benefits in the use of this gas which could result in a good profit in the final analysis.

# QUALITY AND STABILITY FACTORS IN COMPOSTING

## Introduction

The word *compost* derives from the early Latin meaning *to mix or to blend*, and refers to the combination of materials of organic origin into a product known as *humus*. Composting systems have been recognized and described in ancient Sanskrit literature also. More recently, the Howard method and the NADEP[1] method have been proposed. Besides these, there are several ways in which dumping of waste converts it into the so-called compost. This is used by farmers indiscriminately and has now become virtual commerce.

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[1] Process named after Mr N D Pandharipande. He is the inventor of this composting process.

The generally pleasing appearance of finished compost belies the fact that chemically and biologically, they may be unstable and inferior in quality. The reason why one compost may look very good, and another not so good has partly to do with source materials and the qualities they impart to the composting process as well as to the composting or blending method itself and the final degree of maturity.

INORA has been producing and testing composts for the past 12 years, and has now evolved a two-pronged approach to assess the compost quality. One is to analyse source materials and *tailor a recipe* that is expected to perform well. The other is to characterize the final product with a set of chemical, biological, and microbiological tests.

## Appropriate standards

The traditional emphasis on compost quality was confined to metals or human pathogens from sludge or municipal solid wastes (MSWs). This overshadows the fact that compost quality must be characterized in terms of the actual materials being composted and the targeted use. This means that for each type of composting system and set of materials utilized, a set of restriction criteria or *keys* must be identified so that appropriate safety and use parameters can be established.

A summary of a differing set of criteria INORA would attach to composting systems is shown in Table 1.

The dramatic growth of interest in the application of composting for solving the solid waste crisis has surely been noticed by everyone. As the composting horizon is expanding rapidly, the approach also must become more comprehensive.

**TABLE 1.** Criteria attached to different composting systems

| Material | Safety keys | Use keys |
|---|---|---|
| Municipal, industrial sludge | Metals, pollutants, human pathogens | Topsoil amendment |
| MSW (mixed and separated) | Organo-metallic chelates, phytotoxicity | Mulch, nursery blends |
| Fishery and poultry waste, animal wastes | Pollutants, diseases | Nutrient compost |
| Food processing residues/ waste | Plant pathogens, phytotoxicity, soil effects | Nutrient and soil amendments |

Over the past 12 years, INORA has experimented widely in the method of preparing composts from various raw materials with its less-expensive raw material mixing technology. INORA has been researching on three aspects basically.

1. Compost preparation and its variation by tailoring the basic raw materials as feed for earthworms, which is a common mixing, grinding, and maturing system.
2. Testing the quality of the vermicast.
3. Testing the quality of the agricultural and horticultural products with respect to nutritive values, pathogens, and residual chemicals if any.

### Raw *versus* composted waste

Fresh or raw wastes pose problems owing to their odorous and unstable nature. A range of volatile compounds including fatty acids, hydrogen sulphides, ammonia, amines, indoles, and skatoles can be particularly noxious, if they are not properly handled. Odour is an obvious yardstick of quality that will be applied to any compost. But a more important measure of stability is the phytotoxicity or plant growth suppression. Study of field application and the resulting product is therefore important. Many wastes possess phytotoxic traits. The field trials integrate all the parameters to which we can attribute a quality of suppressing plant growth based on watering extracts of composts. Our research indicates that it is primarily the presence of volatile organic acids and oxygen, which cause phytotoxicity. In fact, some composts increase in phytotoxicity during the composting process as a result of inadequate aeration causing a build-up of organic acids such as acetic, butyric, and propionic.

Raw or semi-composted wastes may exhibit negative effects when applied to soil, due to:

1. robbing of available nitrogen if the C/N ratio is greater than 25–30; and
2. growth reduction or phytotoxicity resulting from carry-over of plant pathogens and presence of noxious or incompletely decomposed organic compounds.

In contrast, properly matured composts may exhibit favourable antipathogenic influences when applied to soils, assisting in counteracting root-rot and damping off problems with seedlings and plants. In addition, food product shelf life or the quality of resisting enzymatic-induced deterioration can be significantly increased with use of properly made composts. Such properties have been observed in earthworm-developed composts when all kinds of biodegradable wastes pass through the earthworm gut.

The INORA process uses both aerobic and anaerobic digesting processes before the waste materials in MSW are fed to the earthworm. One of the most important factors affecting metabolism, especially in aerobic conditions, is aeration. Therefore, INORA has concentrated on maintaining good aeration both during the aerobic stage as well as the earthworm composting stage which is the last of the five stages through which MSW is passed. Both the degradation products and the speed of decomposition are dependent on the aeration methods.

Another factor expected to affect the efficiency of compost is the C/N ratio of the MSW. It has been shown that polysaccharides are able to stabilize and improve soil structure. The production of polysaccharides by microorganisms is encouraged when organic carbon supply exceeds the nitrogen availability for protein production. The essential conclusion arrived at was that there is the extreme need to maintain aerobic conditions in the compost mixed soil in order to enhance the oxygen level at the site of the interaction of compost with soil. The earthworms, which come out of the large number of eggs in the compost, serve to maintain the oxygen supply through their burrows as well as casts when aggregated with soil. A large and economically attractive market exists for compost products, particularly for all levels of farmers and horticulturists. This is especially so after the Dunkel proposals, which prohibit the giving of any kind of subsidies by government for chemical fertilizers and pesticides, have been accepted. In the next few years, the trend will rapidly rise in favour of organic composts. The exponential growth of compost-using farmers is clearly seen from their requests to INORA for the earthworm technology, supply of worms and composts, and for training with more information on organic farming.

However, INORA also realizes that this is also the most illusive market because high standards of quality are promulgated here. Therefore, it plans to develop a good laboratory for testing all aspects of compost quality. Over the past eight years, INORA has been researching on the use of composts to formulate different blends, which could completely substitute all kinds of chemicals and pesticides that are available today. Before the compost industry gets a bad name due to unscrupulous producers, INORA wants to establish a standardizing laboratory, which would certify the composts for general and for specific uses.

INORA wants to establish a *soil laboratory with a soul,* and it is on the cutting edge of reducing waste. It continues to offer skilled laboratory services and supplies standardized organic compost with proper certification for its utilization. Besides, it maintains an educational branch of the Institute to promote localization of compost production throughout India. The standards adopted by INORA must:

- safeguard the farmers and gardeners where recycled wastes are used;
- assure the proper end-use of different composts; and

- provide reliable information to make proper environmental laws to help govern the registration of soil amendments.

## Identification

INORA has identified the following composts as *organic,* provided they have passed through the earthworm gut at least once (Table 2). In the INORA process, all these raw materials are used at different stages of pre-digestion before these are finally fed to earthworms. The output from the final earthworm stage is excellent vermicompost. There is no further waste, which means that the INORA process is completely natural, because nature produces no waste.

This process has the advantage of answering our present requirements and also our predictable future needs. It is therefore quite adjustable and can be adapted to varying socio-economic situations. This is an advantage, which cannot be overlooked in the world of sudden and rapid changes. This process is completely indigenous and very flexible for adoption anywhere in the country. Moreover, it needs only low external input, and the output is high. It also requires no energy source and is dependent on labour, creating a minimum of 10 jobs per plant. On the other hand, it generates biogas, which can be used as a source of energy for a large number of purposes.

**TABLE 2.** Different *organic* composts identified

| Compost type | Pre-treatment | Final stage |
|---|---|---|
| Municipal sludge compost | Aerobic and anaerobic | Earthworms |
| Industrial compost | -do- | -do- |
| Msw composts—paper, cardboard, cartons, garbage | -do- | -do- |
| Manure composts—any animal excreta, solid, and liquid | -do- | -do- |
| Food-waste compost from farms, hotels, hostels, industry, slaughter-houses, poultry, fish wastes | -do- | -do- |

## CONCLUSION

The biogas plant, in association with the earthworm compost/culture, forms the basis of the latest eco-industry for the treatment of urban, ordinary industrial, agricultural, and food production waste. The earthworm eco-industry was born during a period of environmental crisis, crisis in agriculture, and the rising crisis in human health. INORA took stock of the environmental problems that need to be tackled in a holistic manner when the scientific and technological measures were put to use. By solving one problem, it was necessary not to create another or several more as a result. It was essential to collect, treat, and enhance the products of this treatment simultaneously causing less pollution.

The INORA process is the result of an integrated series of processes. It takes into account the environmental requirements—no gases, no liquids, and a full control of solid matter. The vermicompost fights soil erosion, helps reduce the use of chemical fertilizers, limits the use of fossil carbon, and is adaptable to the socio-economic needs, thus providing the means to increase and improve horticultural and agricultural products.

### 9

# Lay wasted waste

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## INTRODUCTION

> *There is no field of human endeavour, whether it be in industry or agriculture, or in the preparation of food or in connection with the problems of shelter or clothing, or in the conservation of human and animal health or in the combating of disease, where the microbe does not play an important and often dominant role.*
>
> SELMAN WAKSMAN, 1942

This universal statement, which was made about 50 years ago, failed to emphasize the importance of environmental biotechnology, which has been practised for more than eight millennia [1]. Today, due in part to the advent of pressure groups of so-called *Greens* and *Dark Greens*, environmental biotechnology is rightly recognized in many countries as a research area. Biotechnology, as the Biotechnology Tree (Figure 1; see next page) of Smith clearly shows, is not genetic engineering; but is the application of biological organisms, systems or processes to manufacturing and service industries and the environment [2]. With time, the spectrum of Environmental Biotechnology grows and encompasses such disparate areas as microbially-enhanced oil recovery and mineral leaching, toxic chemical mineralization, microbial corrosion, and waste exploitation.

Prior to the Industrial Revolution, although intermittently practised, waste treatment was not required to any great extent since the demographic distribution, the so-called Z factor, was such that the population was evenly spread and thus microbially-mediated self-purification mechanisms obviated potential deleterious impacts of generated wastes. Even today, at times, these mechanisms offer adequate environmental protection in non-industrialized nations. Thus, for example, in Indonesia, the population, which now exceeds 150 million, is not served by any form of dedicated sewage treatment. Conversely, the growth in volume of increasingly complex waste generated in industrialized nations leaves the environment ever more vulnerable. Here, it is worth noting that between 50

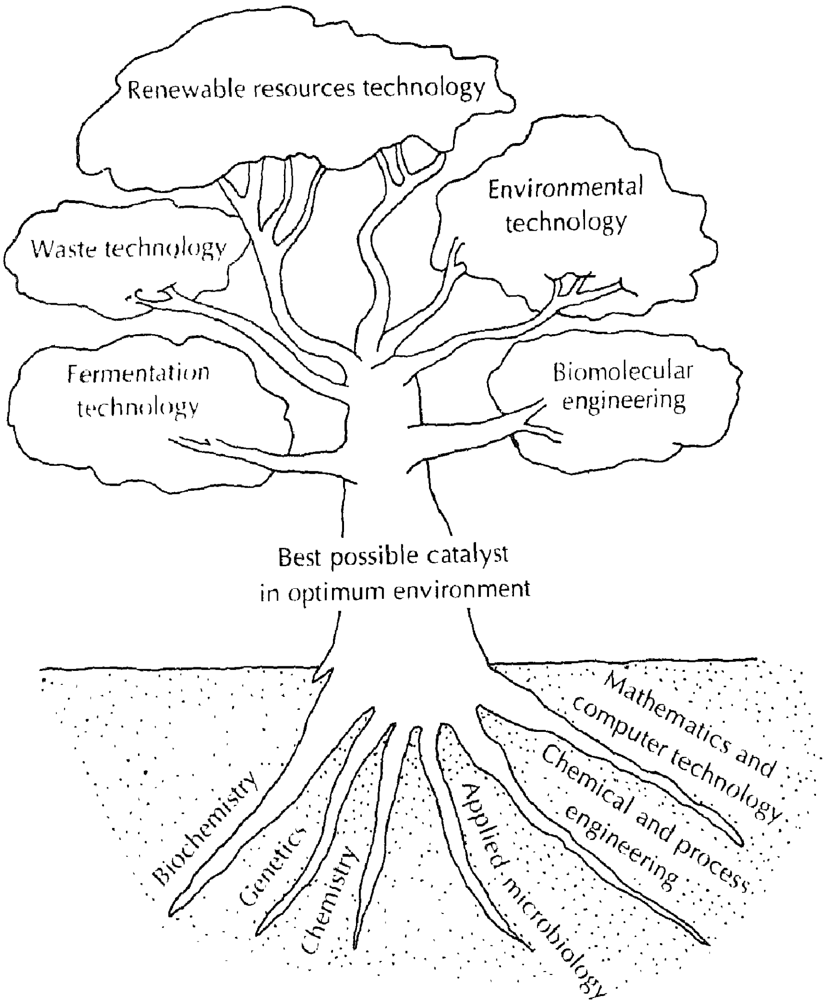

Renewable resources technology
Environmental technology
Waste technology
Fermentation technology
Biomolecular engineering
Best possible catalyst in optimum environment
Biochemistry
Genetics
Chemistry
Applied microbiology
Chemical and process engineering
Mathematics and computer technology

**FIGURE 1.** The biotechnology tree.
*Source.* Smith J E. 1981. *Biotechnology.* London: Edward Arnold.

and 60% of all raw materials used in chemical synthesis ultimately becomes waste. In 1980, the World Health Organization estimated that four million chemicals had been either isolated from natural products or had been synthesized. Of these, about 60 000 were thought to be in daily use and 200 new chemicals were, then, marketed each year. Unfortunately, this figure has now increased to 1200 per year. Many of these compounds have been labelled *hazardous* or *toxic*. In USA, the Environmental Protection Agency has classified more than 48 500 chemicals as *toxic*. In terms of volume, USA now generates 265 million tonnes of *hazardous* wastes each year, which is more than double the municipal waste total. It is estimated that 60–90% of all cancer cases are of environmental origin. Unfortunately, of the identified toxic chemicals, less than 20% have been evaluated for their environmental impact. As a consequence, very little recycling is practised. Thus in UK, for example, 1250 manufacturing plants have been classified as *high risk*, yet there is little or no recycling. In Germany, several hundred thousand tonnes of toxic wastes are discharged into the River Rhine each year, notwithstanding the fact that 20 million people rely on the same river for their water supply. Lack of treatment is particularly evident in the European Community, where 30 million tonnes of *toxic* wastes are generated each year. This figure represents more than three times the existing treatment capacity and, as a consequence, more than 30% of the wastes cross international frontiers.

In South Africa, unfortunately, the information available is somewhat sketchy. However, a clear picture should hopefully emerge with the report of the Hazardous Waste Panel, convened by the Foundation for Research Development for the Department of Environmental Affairs.

With so many problems recognized, the search for novel and efficient recycling processes and innovative waste disposal strategies is gathering some momentum and is motivated by the need both to conserve finite natural resources and to negate deleterious environmental impacts of the expanding array of pollutants.

For industry, although returns on investment will often favour product research to the exclusion of pollution control, the rising costs of raw materials and the depletion of non-renewable energy sources have resulted in a polarization away from simple environmental control (waste treatment) to consideration of potentially profitable alternatives such as generation of energy, value-added chemicals, chemical feedstock or protein.

Exploitation of waste is, however, nothing new. For example, 4000 years ago in the city of Knossos in Minoan Crete, circular-walled pits (Kouloura) were used as bioreactors for the composting of refuse to produce a nitrogen-rich product [1]. In Tudor England, the same basic biotechnology was employed to produce saltpetre equivalent for the subsequent manufacture of gunpowder. Here, the practice was to discard domestic residues directly onto the floor of the dwelling until a depth of almost a metre was reached. At this point, the partially-decomposed refuse was removed and transported to caves where it was supplemented with blood, urine, and wood ash. The mixture was then allowed to ferment for up to two years to produce the required product. This practice continued for more than 100 years until the mid-seventeenth century when Indian imports rendered the biotechnology obsolete [3]. Although relatively successful, the above processes were reliant to a considerable extent on serendipity. Even today, this element of chance is still a major factor in many waste disposal/exploitation strategies. Perhaps the intimidating complexity of essential microbiology has been a causal factor here despite the fact that elucidation of the complex interspecies interactions of the responsible interacting microbial associations represents a conceptually stimulating challenge.

But for how long can this element of chance be tolerated? Life is a total paradox. For example, we would never consider administering any pharmaceutical products, real or placebo, before knowing that it had been carefully researched for the specific purpose. But for wastes, *out of site out of mind* is the norm and the not in my back yard (NIMBY) syndrome is the only one which invokes any kind of sustained response.

Increasingly, consciences are appeased by contributing to paper or bottle banks or by buying *environmentally-friendly* products, but the fundamental causes of the problems are rarely considered. Given the choice, majority of the public would prefer to be embarrassed into buying a flag to support medical research rather than pollution control. This is clearly seen at the government level, where millions of dollars are poured into cancer research while the major causal factor, the polluted biosphere, receives derisory token funding.

The problems and challenges of waste biotechnology thus remain and continue to grow. Nowhere is this challenge greater than with the fermentation of refuse. This is the oldest of all practised solid-state fermentations—landfills—with archaeological remains of both classical Mediterranean and northern European civilizations located on sites. Despite such early beginnings, it was not until the mid-1930s that regulated tipping to landfill became the norm in many industrialized nations, thereby controlling the associated biotic, chemical, olfactory, and aesthetic problems to a considerable, but still disputable, extent.

Landfill is defined as *a land disposal site at which is employed an engineered method of disposing solid wastes in a manner through which environmental hazards are minimized by spreading the solid wastes to the smallest practical volume and applying a compacting covering material at the end of each operating day.* This practice is characteristic of most developed countries, with controls being administered through planning approvals and site licences. It is perhaps surprising that despite increasing national and international legislation, uncontrolled tipping in 1984 still accounted for 10.3, 19.5, and 35% of the total wastes disposed in France, Greece, and Ireland, respectively [4].

Although significant developments in alternative technologies have been made, landfill will continue to be an essential element in the management of solid wastes, particularly the waste residues resulting from other treatment strategies. On a cost basis, landfill disposal is relatively cheap, often representing a saving of 65% or more when compared with alternatives (composting, incineration, pyrolysis, gasification or pressure liquefaction). In addition, properly managed landfill, with re-establishment of landscape contours and restoration of low-lying land, can add considerably to land values.

Although low-cost disposal is the essential objective, the landfill bioreactor may be regarded as providing any or all of the following.

- An ultimate disposal option, which may still require the provision of further treatment facilities for generated liquid products (leachate).
- An aerobic reactor for carbon dioxide generation.
- An anaerobic filter for industrial liquid and sludge effluent treatment (co-disposal).
- An anaerobic digester for methane, chemical feedstock or value-added chemical generation.

Like many biotechnologies, exploitation of the refuse fermentation is dependent on three factors—the substrate, the bioreactor, and the degree of control administered. Like other biotechnologies, the fundamental microbiology must be researched to a high degree and no compromises must be made.

## LANDFILL SUBSTRATES

The composition of refuse is particularly difficult to generalize since dramatic changes are seen from country to country, from culture to culture, and with time [5]. Even within the increasingly homogeneous European Community, major differences are apparent—northern European refuse is dominated by high paper and plastic contents but low putrescibles, while those of southern Europe contains higher proportions of organic and fine materials and combustibles (Table 1) [6].

**Table 1.** Analysis of domestic refuse (% w/w) of Germany, the Netherlands, Oslo, Rome, and Madrid

| Refuse | Proportions of refuse (% w/w) | | | | |
|---|---|---|---|---|---|
| | Germany | The Netherlands | Oslo | Rome | Madrid |
| Paper/cardboard | 22.7 | 22 3 | 38.2 | 25.0 | 15 |
| Organic, putrescibles and fines | 45.6 | 53.0 | 30.4 | 53.0 | 50 |
| Plastics | 08.4 | 06.8 | 06.5 | 06.5 | 05 |
| Miscellaneous combustibles | 03.9 | 03.7 | 15.4 | 03.0 | 18 |
| Glass/other non-combustibles | 12.8/2.9 | 08.1/2.6 | 07.5 | 01.0 | 09 |
| Ferrous metal | 03.7 | 02.5 | 02.0 | 02.5 | 03 |

*Source* Barton J R, Poll A J, Webb M, Whalley L. 1985. *Waste Sorting and RDF Production in Europe*. London: Elsevier Applied Science Publishers.

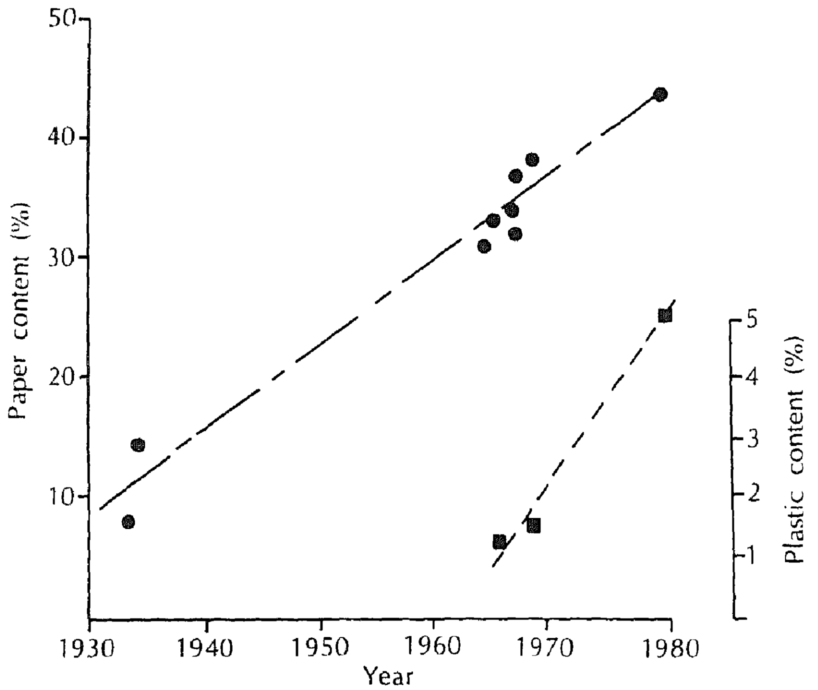


**FIGURE 2.** Changes in the paper and plastic content of domestic refuse.
*Source.* Forster C F, Senior E. 1987. Solid waste. *Environmental Biotechnology*, edited by C F Forster and D A J Wase. Chichester: Ellis Horwood.

Analytical data are usually available only for developed countries, and even here, direct comparisons are difficult to make since the classification systems used differ. For industrialized nations, however, three distinct changes have been seen with time. Firstly, the volume of refuse produced per head has increased and continues to do so. Secondly, the proportion of the biodegradable refuse has increased. This is particularly apparent in temperate regions where the decreasing importance of domestic coal-fired heating has led to a reduced ash content. Finally, the paper, card, and plastic contents have also increased to a combination of reduced fire burning in homes and changes in marketing with the increased use of disposable packaging (Figure 2).

A typical domestic refuse analysis, characteristic of an industrialized nation, is shown in Table 2, and its more important elemental analysis in Table 3.

As a consequence of the historical changes discussed above, the carbon-to-nitrogen ratio of the organic fraction of refuse at tipping may often exceed 55:1. Such values will mean that the nitrogen content may prove limiting to the microorganisms responsible for aerobic (composting) and, to a lesser extent, for subsequent anaerobic breakdown. However, since the fixation of atmospheric nitrogen

**TABLE 2.** Domestic refuse components

| Components | % w/w |
|---|---|
| Dust, cinder, ash | 14 |
| Vegetables, putrescibles | 25 |
| Paper, board | 29 |
| Textiles | 3 |
| Metals | 8 |
| Glass | 10 |
| Plastics | 7 |
| Unclassified | 4 |

**TABLE 3.** Refuse elemental analysis

| Refuse element | % w/w |
|---|---|
| Carbon | 25.5 |
| Nitrogen | 0.5 |
| Hydrogen | 3.4 |
| Oxygen | 20.3 |
| Sulphur | 0.2 |
| Chloride | 0.5 |
| Water | 25.2 |
| Inorganics | 24.4 |

by microorganisms within the refuse mass may make a significant contribution to the biologically-available nitrogen pool, it may be that the low concentrations of phosphorus will ultimately prove to be limiting. In either case, to avoid a need for an unduly protracted period for stabilization and, hence, settlement of the landfill, some form of nutrient supplementation, for example, by the addition of nitrogen and phosphorus-rich sewage sludge, may well have to be considered. With changes in international legislation on ocean dumping of sewage sludge, disposal of this residue to landfill may soon become the norm. However, since the insidious environmental impact potential of generated liquid (leachate) already invokes considerable concern, the possibility of elevated ammonium concentrations due to bacterial denitrification processes should be addressed [7].

Various pretreatments of refuse will subsequently result in significant changes in refuse breakdown (fermentation balance) and hence, products formed [8]. For example, milling, shredding, and pulverizing dramatically increase the refuse surface area and, at the same time, facilitate significant oxygen ingression. Conversely, baling eliminates air and promotes anaerobiosis.

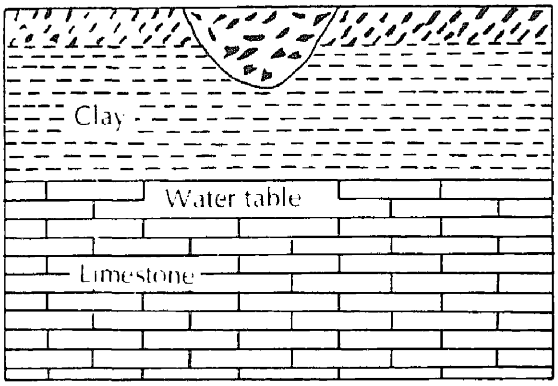
## THE LANDFILL BIOREACTOR

Operational landfills, which are becoming fewer but larger, vary enormously in size, i.e., from a few acres up to New York City's 1500-acre Fresh Kills Landfill located on Staten Island. Depths can also vary from one or two metres to 100 metres or more [9].

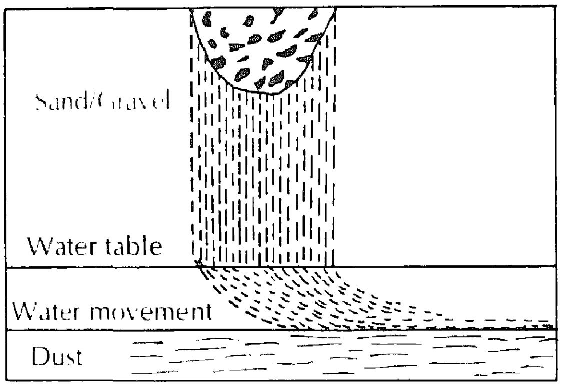
The essential design for landfill site selection is protection of ground or surface waters from the leachate which drains from the refuse mass (Figure 3). In Class I sites, this is achieved by providing barriers of natural (clays, sodium bentonite, and fine grain soils) or artificial (polymeric membranes, concrete, soil/cement mixes, and asphalts) materials. However, it must be recognized that unless provision is made to reduce infiltration into such sites, and to collect and dispose of the generated leachate, the refuse will eventually become saturated. Any leachate escape may thus result in surface or groundwater pollution. For Class I sites, it is essential that the liner should preserve its integrity for many years since whereas typically, sites may be used for, say, between 5 and 10 years, the half-life of refuse decomposition (50% breakdown) is closer to 60 years. Choice of material is, therefore, particularly important since each has its advantages and disadvantages. Consideration should also be given to the selection of sites with relatively stable geology and the use of models, which have been developed to aid design of landfill liners [10].

Although cheap natural materials such as clay, with hydraulic conductivities (coefficients of permeability) less than $10^{-7}$ cm/s, are usually considered suitable for long-term containment provided the thickness of the liner approaches two metres, there is no demonstrated evidence of their efficacy over protracted periods. Before using clays, their hydraulic conductivities must be measured *in situ* since these values have been shown to be up to 1000 times greater than laboratory results with either undisturbed or recompacted samples of the same material [11]. Since the moisture content of clays remains high, the conductivity decreases only slowly with increasing moisture tension. So even under unsaturated conditions, the seepage rate (typically 1 cm every 116 days) remains relatively high [12]. This is particularly true for basic (aniline), neutral (methanol), and neutral nonpolar (xylene) components of leachates, which effect conductivity-increases by orders of magnitude. Unfortunately, interaction of clays with the same chemicals may cause structural changes, with the result that shrinkage and cracking or swelling may occur [13]. Thus, the liner may weaken or even fail.

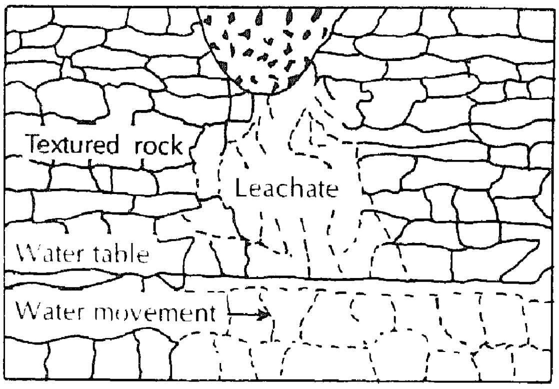
An alternative natural liner material is the mineral sodium bentonite, which swells in the presence of water to absorb nearly five times its dry weight occupying a volume up to 15 times its dry bulk with full saturation [14]. In the presence of soil, this swelling process plugs the net voids and a very flexible liner is created, which has a hydraulic conductivity of $10^{-8}$ cm/s. The natural properties



**Class I** (containment site). The refuse and leachate are contained within the landfill by an impermeable or semipermeable barrier such as clay.



**Class II** (attenuation site). Sand and gravel allow slow leachate migration with significant attenuation; an underlying impermeable shale barrier protects deeper aquifers.



**Class III** (rapid migration site). Fissured strata allow rapid leachate migration, with little attenuation, into the aquifer.

**FIGURE 3.** Landfill site categories.
*Source.* Senior E 1990. Introduction. *Microbiology of Landfill Sites*, edited by E Senior. Boca Raton: CRC Press.

of the mineral, which include high base exchange capacity, may be enhanced with patented chemical treatments, which increase expandability. In general, sodium bentonite liners (10–15 cm thick) are not subject to sudden failure.

Although the use of synthetic materials, such as flexible membranes, is an expensive method of lining landfills, their hydraulic conductivities may be as low as $10^{-12}$ cm/s, with permeability to the depth of 1 cm taking 31 688 years [12]. However, sheet liner imperfections do occur. Thus, geophysical techniques, based on electrical resistance, have been developed to detect leaks as little as 2 cm and to locate these to within 30 cm. Despite this accuracy the problem of access to the hole to effect the necessary repairs remains. To prevent puncture or abrasion of synthetic liners, compositions such as *Monarflex 500*, which is a polythene membrane (0.5 mm thick) reinforced with polyester fibres, or thick, strong permeable geotextile overliners may be considered [15, 16]. In addition, covers of soil, at least 35 cm thick, are required to protect the liners from landfill operations.

Polythene is resistant to acids, bases, and salts at the concentrations usually encountered in refuse; but plastics are susceptible to microbial attack, particularly when the component monomers are small. In the case of chemical attacks, swelling occurs, which, in turn, may lead to softening, loss of strength and elongation, increased permeability and creep together with increased susceptibility to polymer biodegradation. Since membranes have little capacity to absorb and attenuate pollutants, failure may result in unrestricted leachate flow [14]. Thus, due consideration should be given to all possible causes of liner failure, which includes physical (puncture, tear, creep, freeze-thaw cracking, wet-dry cracking, differential settling, thermal stress, hydrostatic pressure, abrasion), biological (microbial attack), and chemical (ultraviolet light attack, ozone attack, hydrolysis, ionic species challenge, extraction, ionic species incompatibility, solvents) factors.

Despite these potential problems, Class I sites are now gaining popularity in industrialized nations, thus following the lead of Germany. In countries, which are heavily reliant on groundwater for drinking water supply, aquifer protection by containment site operation is a must. Thus, for example, in USA, which obtains 50% of its water from groundwater sources, double liners of synthetic material, together with leachate collection systems, are now the norm. Although South Africa has a low groundwater dependency, effective liners should be encouraged and should not be regarded as a luxury.

As an alternative in aquifer protection by containment, Class II sites rely on attenuation mechanisms. These sites are situated on sand or gravel and slow leachate migration through silt facilitates its attenuation by microbiological and physico-chemical (filtration, absorption, ion exchange, and precipitation) process. This type of site is often favoured by the landfill contractors since accumulation of water in the fully-contained Class I sites could cause obvious problems.

Finally, there are Class III sites, which offer little environmental protection since the generated leachate migrates rapidly through fissured strata with only limited attenuation.

Whichever class of site is selected, siting and operations must not be intrusive in the area or detrimental to residential properties in the vicinity. Also, any initial environmental impact should be minimized by the waste placement strategy adopted and the continuing establishment of present and future landscaping.

## Compost pile or landfill?

The most economic method of waste disposal other than a landfill is probably some form of composting. Although there is a growing global demand for compost to rehabilitate impoverished soils, the economic viability of composting municipal refuse as a sole mode of reclamation has been questioned. Development work has, however, continued in Western Europe, Japan, and USA. Unfortunately, the repeated use of refuse compost from industrial/urban communities on agricultural land can result in contamination with heavy metals to the detriment of both the soil and the crop.

The methods of refuse emplacement and site management do differ, but the trend is to move increasingly away from the traditional tip towards covering the refuse, which may be of domestic, commercial or industrial origin, at the end of each working day.

Usually, the refuse is deposited on the surface of the site behind the face (maximum length 20 m) and partially compacted before being pushed over the face. Alternatively, the waste is deposited on the ground forming the base of the site, or on a previous layer in front of the face, and is formed into a compacted layer by being pushed upwards and driven over by a compactor. Before covering (to a depth of not less than 1.5 m), the working faces and flanks are compacted to form gradients of one in three or less to encourage surface water run-off.

With time, this *cell* system of tipping creates a multiplicity of partially separated (spatially and temporally) solid-state closed (batch) cultures, with limited oxygen content, throughout the bioreactor. The end result is an extremely complex and spatially heterogeneous ecosystem, which contains both vertically and horizontally organized components, all of which are subject to changes with time. Key components here include multidirectional gradients in temperature, gas–liquid redox potential ($E_h$), pH, enzyme activity, electron acceptor, and solute flow. For a complete description and characterization of the ecosystem, properties at the molecular level, such as water solubility, lipid/water partition coefficient, volatility, molecular size, charge, shape and functional group presence, microbial attachment to organic and inorganic surfaces, and interspecies interactions and interfaces should also be considered. The fact that no such description is really feasible not only emphasizes the empirical basis of most contemporary practices, but also draws attention to specific aspects of the problem which might otherwise be overlooked.

## Refuse decomposition

The main points of refuse decomposition have been highlighted below [17]. To date, there has been such a paucity of definitive studies on refuse catabolism that extrapolations have had to be made from *comparable* ecosystems. In the solid-state refuse fermentation, multiplicities of reactions are often required to effect conversions of natural polymers, particularly lignocellulose to metabolic intermediates and end products (Figure 4). The essential criterion for all potential substrates for microbial metabolism is that species must derive energy and cellular constituents from the oxidative metabolism of the compounds. Thus, not all components of refuse constitute substrates for the fermentation, and those which do may become semi-recalcitrant or even recalcitrant if physiological conditions change. This is particularly true of heterogeneous macro-molecules which, although dissimilated

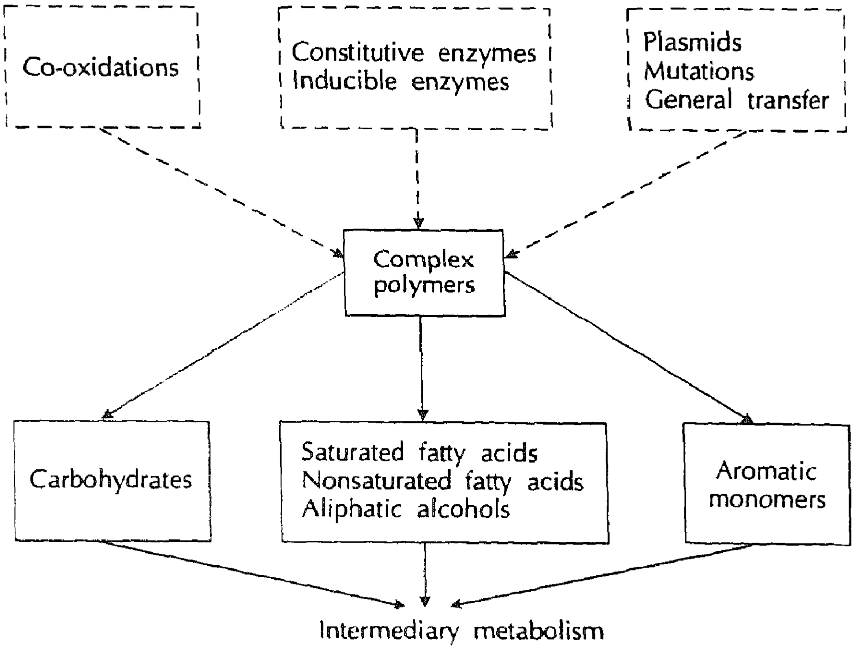


**Figure 4.** Catabolism of polymeric refuse components.
*Source.* Senior E, Balba M T M 1990. Refuse decomposition. *Microbiology of Landfill Sites*, edited by E Senior. Boca Raton. CRC Press.

slowly under aerobic conditions, in the absence of oxygen are effectively (biologically) inert.

### Aerobic catabolism

Initially, refuse catabolism, accompanied by physical and chemical reactions, is dominated by aerobic process and involves a whole range of organisms including invertebrates (mites, millipedes, isopods, nematodes, euchytraeids), which ingest organic materials, together with bacteria including actinomycetes, and fungi. Food webs become established, which include different trophic levels. For example, collembolans and ptilids feed on fungal mycelia and spores, respectively, while nematodes, protozoa, and rotifers ingest bacterial cells.

In this phase, labile molecules are rapidly degraded, often mixotrophically. Subsequently, macro-molecules such as lignocellulose, lignin, tannin, and melanin are dissimilated provided oxygen does not become limiting. The actual length of this period varies considerably and, in part, depends on the primary processing described earlier.

Although various methods may be employed to monitor the extent of decomposition, arguably the most successful depends on the differing rates of catabolism of cellulose and lignin [18]. Thus, cellulose:lignin ratio estimates of 4.0, 0.9–1.2, and 0.2 have been reported for unfermented refuse, active or partially stabilized landfill, and well-stabilized landfill, respectively, as the lignin component becomes progressively more recalcitrant.

Overall, aerobic metabolism of refuse results in the formation of a whole range of chemical intermediates together with terminal products such as stable humic compounds, carbon dioxide, and water. During this stage, exothermic reactions result in a temperature increase (up to 80 °C), which together with the presence of abiotic antimicrobial molecules, result in the death or inactivation of pathogens such as *Salmonella* spp., Polio Virus type 1, insect larvae, and plant seeds [19]. Thus, landfill is not a seething mass of pathogens as is often feared. Although the initial temperature-increases have a positive direct effect of accelerating microbial activity and growth, these physiological promotions are challenged by the indirect negative effect of reduced solubility of the limiting oxygen. Carbon dioxide, in turn, can also influence metabolic rate by effecting a pH reduction, although this can, in fact, promote polymer hydrolysis.

Finally, the significant production of water by microbial metabolism can add considerably to the site water balance [20].

### Anaerobic catabolism

The *in situ* depletion of molecular oxygen results in slowing down of heat production, and oxygen entry by convection is correspondingly diminished. With the concomitant accumulation of carbon dioxide, microaerophilic conditions are established, which provide the selection pressures for the enrichment of facultative anaerobic bacteria first, and then, of obligate anaerobes as the redox conditions become suitably reduced. Perhaps it is fortunate that these species do not suffer from the same nitrogen and/or phosphorus element mutation as do the aerobes, and so the catabolic processes continue. Unlike aerobic metabolism, where complete mineralization is often achieved by a single bacterial species, anoxic dissimilation, characteristically, requires the co-operative metabolism of a mixed population. Each component species of these microbial associations contributes a partial oxidization of the particular compound until the terminal products of carbon dioxide and methane result. Mobilization of multi-species gene pools in this way is the major integrity determinant of the closely interacting, highly-stable, mixed substrate-utilizing populations. Despite this stability, however, the associations are still strongly influenced, both positively and negatively, by chemical gradients of electron donors and acceptors, and by hydrogen concentrations.

In the absence of molecular oxygen, these interacting associations are able to use a variety of inorganic electron acceptors, such as nitrate, sulphate, and carbon dioxide, often in sequence, according to the energy liberated from a common electron donor [21]. Since most of the bacteria specialize in using a specific electron acceptor, the sequence of use leads to distinct changes in bacterial populations. Species, which are able to use more oxidized acceptors, gain a thermodynamic advantage which usually manifests as a kinetic advantage. Thus, for example, although sulphate-reducing bacteria and carbon dioxide-using methanogens are able to occupy similar ecological niches, if they are competing for the same limiting substrate(s) (hydrogen and/or acetate), then the former species should competitively displace the latter, due to their higher affinities for both the molecules, until the sulphate becomes exhausted. In reality, the picture is much more complicated than this as kinetic considerations, substrate uptake, and subsequent transport all play key integral roles.

Due to similarity of products generated in the microaerophilic and anaerobic phases, it is extremely difficult to distinguish between these two in practice, although both make major contributions to the overall decomposition processes.

Although no data are available on anoxic refuse catabolism, it is possible to make schematic pathways from other anoxic ecosystems. For convenience, the sequences may be divided into hydrolysis, propionogenesis, acetogenesis, and methanogenesis. However, compartmentalizations such as these do fail to capture the dynamics of the reactions.

### *Hydrolysis and fermentation*

During this stage, fermentative bacteria (which require no external electron acceptor and, therefore, do not depend on gradients of acceptors) hydrolyse polymers such as polysaccharides, lipids, proteins, and nucleic acids and ferment the resulting monomers to gaseous metabolites such as hydrogen and carbon dioxide, and to straight- and branched-chain fatty acids together with compounds such as ethanol, lactate, and succinate. Product distribution of individual compounds can vary considerably and is dependent on a number of interrelated factors such as redox potential, specific growth rate of microbial species, molecular configuration, and hydrogen concentration. Close interrelationships are often found between fermentative bacteria and bacteria catabolizing the resulting products—hydrogen and acetate [22]. Such relationships are often essential since fermentation reactions are thermodynamically feasible only at very low concentrations of hydrogen. Even where no inhibition is apparent, hydrogen concentration often influences the reaction. At low concentrations, for example, the fermentation balance is shifted towards more oxidized products (particularly acetate), and more of the energy of the reaction is conserved as adenosine triphosphate (ATP), an effect also seen where low concentrations of lactate are maintained. Both sulphate-reducing and methanogenic bacteria thus play key roles by removing toxic metabolites, directing electron flow to reduced end products and enhancing growth rates, while, supplying essential growth factors at the same time [23].

### *Propionogenesis*

Propionogenic bacteria are an important group of hydrogen-consuming species, particularly under mildly acidic conditions in the presence of limited concentrations of sulphate. Thus, although unquantified as yet, they may prove to play significant roles in the landfill ecosystem.

### *Acetogenesis*

Two distinct types of bacteria are responsible for the generation of acetate—the hydrogen-producing acetogens, which gain energy for growth by dissimilating alcohol and organic acids into acetic acid and hydrogen (and occasionally carbon dioxide), and the hydrogen-consuming homoacetogens, which catabolize carbohydrates, hydrogen, and carbon dioxide or one-carbon compounds into acetic acid. The major difference between the two types of acetogens is that the former, for thermodynamic reasons, must grow in dual culture with an obligate hydrogen-sink bacterium, which maintains a low partial pressure of hydrogen in the ecosystem; otherwise inhibitory concentrations of reduced organic acids would accumulate. At times, this could possibly be regarded as beneficial since acid hydrolysis of refuse polymers would be promoted.

### *Methanogenesis*

Chemical analysis shows that the refuse mass is not characterized by the presence of high concentrations of inorganic electron acceptors other than carbon dioxide.

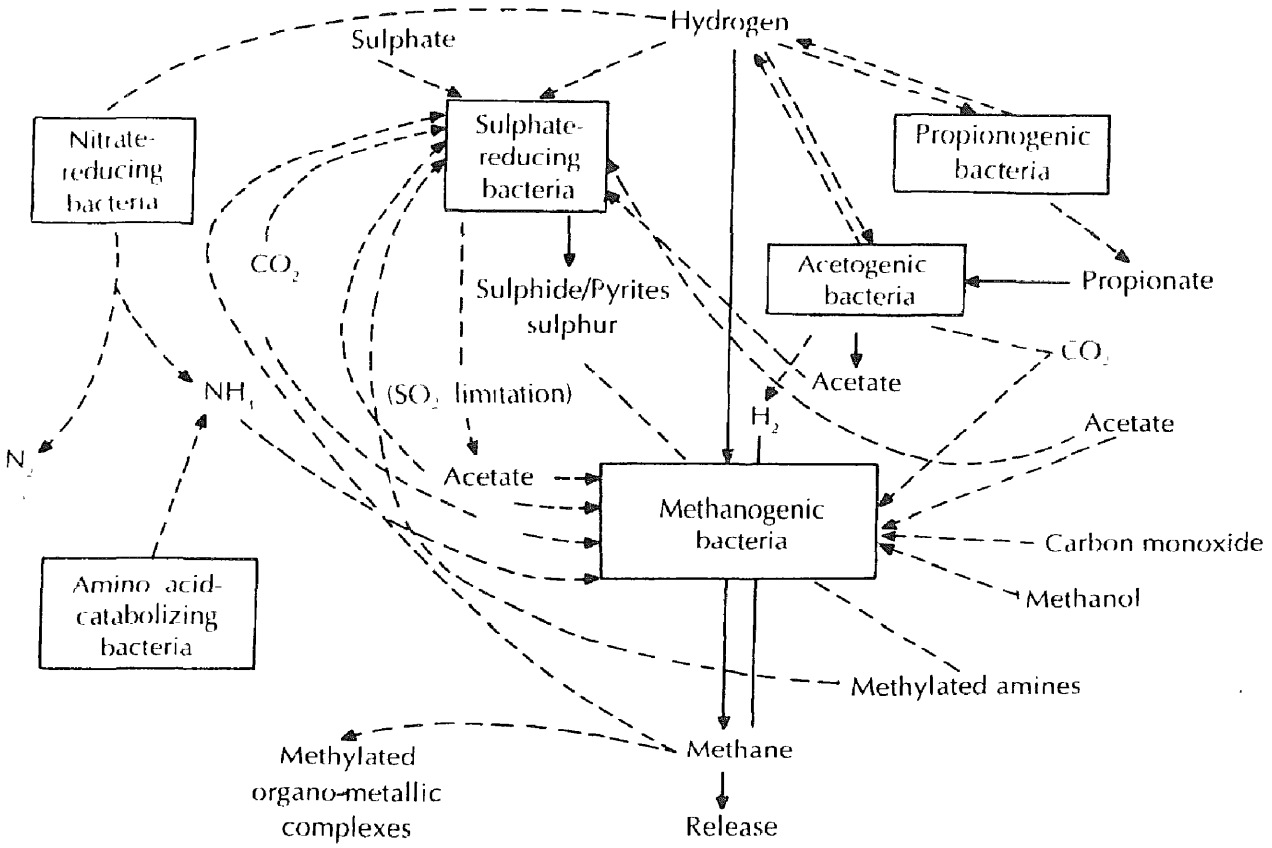


**FIGURE 5.** Microbial interactions in terminal anoxic catabolism.
*Source*. Forster C F, Senior E. 1987. Solid waste. *Environmental Biotechnology*, edited by C F Forster and D A J Wase. Chichester: Ellis Horwood.

The carbon dioxide-utilizing methanogens must, therefore, play key bioregulatory roles (proton, electron, and nutrient regulation) in the refuse fermentation.

Proton regulation may be effected by removal of potentially toxic metabolites such as acetate, methanol, *iso*-propanol, formate, and methylated amines. Much work remains to be done in this area since, to date, only four (carbon dioxide/hydrogen, acetic acid, methanol, and trimethylamine) methanogenic pathways have been confirmed in landfill [24].

The key to actual products generated during anaerobic microbial catabolism of refuse is the interactions between the different microorganisms as directed by the electron donor and electron acceptor components of the material [17]. Although this is still very much a black box, complete understanding of the interspecies interactions is an essential prerequisite for the identification of rate-limiting steps, and thus, ultimate control/optimization of the refuse fermentation (Figure 5).

## LANDFILL FERMENTATION CONTROL

Often total control of the landfill bioreactor, for example, to control leachate generation or inhibit or promote methane generation, is still, at best, tenuous. Many of the possible manipulations can only be made indirectly and in ways which will not interfere with daily site operation. Within these constraints, possible points through which the refuse fermentation may be manipulated include the pretreatment strategy and *in situ* control of density, temperature, moisture content, pH, and alkalinity, as well as by site *seeding* and nutrient supplementation.

### Moisture content

The moisture content of the emplaced refuse plays a key role in its metabolism, and some manipulation of the solid-state fermentation may be effected by control of the site water balance, which may be simply expressed as:

$$P = R + E + W,$$

where P is the average site catchment precipitation (at least 50% of the annual rainfall falling on an operational site will infiltrate); R is the average site run-off, which may be controlled by the topography of the emplaced refuse and by the final restoration strategy; E is the mean site evaporation and transpiration (this is promoted by the type of vegetation cover and by the temperature of the refuse mass and can account for as much as 30% of the initial precipitation); and W is the mean storage change over the site.

In typical field situations, the absorbent proportion of emplaced refuse has a water capacity of approximately 55% (w/w). During periods of short heavy rainfall, however, the maximum absorption (infiltration capacity) may be exceeded before the field capacity has been reached, thus resulting in the release of leachate from both Class II and Class III sites. This can be a problem in the tropics during the monsoons.

Although optimization of the water content for solid-state fermentation is relatively straightforward in the laboratory, in field situations, it must be recognized that *in situ* water is not homogeneously distributed but is held in the refuse mass in three forms—gravitational, capillary, and hygroscopic [25]. Capillary and hygroscopic waters are held in micropores and void spaces, whereas gravitational water is often present in macrovoids between refuse components and, as such, may result in the formation of perched water tables.

There can be three different objectives in attempting to control the site water balance. They are: (i) to optimize methanogenesis; (2) to inhibit methanogenesis; and (3) to minimize leachate production.

### *Optimization of methanogenesis*

Landfill methane represents a reservoir of tremendous potential, which is relatively untapped. There are now more than 250 commercial landfill gas exploitation schemes in operation around the world, contributing more than 500 million tonnes of coal equivalent per annum to energy requirements. This figure is set to rise, so that 70–80 million tonnes of coal equivalent can be recovered as methane in landfill gas each year. As a bonus, the otherwise insidious contribution of methane to the greenhouse effect (on an equivalence basis methane is 27 times more powerful than carbon dioxide) will be reduced.

The actual size of sites from which gas is commercially extracted vary enormously in terms of acreage and depth. In USA, for example, the sites vary from 6 to 600 hectares (average 68) [26] and from 6 to 90 m (average 30) deep [27]. In contrast, the European sites tend to be smaller and may be as little as 10 acres.

Feasibility of commercial gas extraction is often based on the satisfaction of specific site criteria—one to two million tonnes of in-place refuse; an average refuse depth of 12 m; an active fill area of 16 acres; a refuse intake of 400 tonnes per day; the landfill either recently closed or, preferably, still active; and a market for the gas in close proximity [28].

Theoretical estimates of methane production from refuse have ranged from 16 to 450 l/kg/year. If these figures are critically evaluated, a reasonable rate during the more active period of methane production would be between 3 and 37 l/kg/year. The efficacy of microbial methanogenesis can be gauged by comparison with energy recovery from refuse by incineration and pyrolysis, which would be 10 and 5 times higher, respectively. These figures, however, must be balanced against the much lower construction and running costs of the landfill.

The role of water in optimizing methanogenesis involves two separate variables—the water content as such and its movement through the refuse mass [29]. A number of studies have been made to determine the percentage water content required for optimum gas production with values between 55% (w/w) and water-saturated conditions (99% as dry weight) reported [30, 31]. Laboratory experiments have shown that an increase in moisture content from 55 to 75% (w/w) can effect a 2.4-fold increase in the total volume of methane evolved during a measured study period (95 days) [25]. Perhaps of more significance was the finding that at moisture contents above 60%, the methanogenic rates were independent of the moisture regimes and high moisture contents (>80%) proved inhibitory. Results such as these have important implications *in situ* since many sites extend below the water table and so the potential of the methanogenic fermentation may not be fully realized. High moisture contents do however mediate percentage methane content increases due to enhanced dissolution of carbon dioxide. This, in turn, may result in a lowering of the gross pH and, thus, a slowing of methanogenesis.

It must be recognized, however, that percentage moisture content values are inappropriate without reference to the density of the emplaced material. Work in Belgium has shown that incremental increases in the moisture content produce more pronounced changes in low density (0.25 t/m$^3$) than in compacted (0.80 t/m$^3$) refuse. Similarly, work in UK showed that a doubling of refuse density prior to saturation with water can result in a 50% reduction of the gas production rate. The inference here is that lower density refuse facilitates increased bacterial mobility which, in turn, promotes the fermentation. Whilst plausible, this explanation does not account for the converse situation where, under conditions of a constant moisture content (21%), a density increase from 0.32 to 0.47 t/m$^3$ was shown to result in a doubling of the gas production rate [31].

Although the effects of the interdependent factors of refuse moisture content and density are still not fully resolved, it appears from laboratory studies and calculations of activation energies that at high moisture contents, the overall reaction rate is chemically controlled and is independent of diffusional mass transfer limitations [25]. Elevated moisture contents can, however, result in significant changes to the fermentation balance, particularly the disappearance of hydrogen, which is a characteristic of unsaturated refuse fermentations.

Despite control difficulties in a practical sense, moisture movement through the refuse mass has been shown to accelerate methanogenesis (with rate increases of between 25 and 50%). Even in a constant moisture content regime, further increases were apparent when the water was replaced by leachate [29].

Controlled water addition is a key element in site strategies developed to promote methanogenesis. It has been advocated, for example, that either low density refuse (0.35 t/m$^3$) should form the base of the fill, and should be allowed to compost with either wood or paper, or, alternatively pulverized refuse should be used after first diluting it with either aerobically stabilized refuse or other inert materials [32]. Subsequently, controlled water additions should be made to a discrete site area at the base of the fill through a central well and should be allowed to rise at a rate of 1–2 m/year with the objective of keeping the acidogenic and methanogenic phases in balance. Further elements of the strategy were the provision of an insulating layer of refuse to prevent both heat loss and the possible ingression of air, and the possibility of site seeding with anaerobic digester sludge.

Once formed, it is essential that methane be removed to prevent possible product inhibition or reoxidation to carbon dioxide by anaerobic species such as sulphate-reducing bacteria or methanogens themselves, or by aerobic methanotrophs.

Simple venting systems are not always conducive to collecting the methane for fuel use, which will normally require a more elaborate gas-handling system. It must also be recognized that there may be major gas losses, for example, between withdrawal wells or near landfill boundaries. Typically, landfill gas may be recovered by means of vertical or horizontal perforated pipes or domes of polythene sheeting. Vertical wells, for example, are sunk into the refuse and are then connected together by horizontal polythene or PVC pipes. Pumps or blowers may then be applied to increase the recovery efficiency although care must be taken to prevent suction of air into the refuse mass [33].

Although site water additions have been used in practice, major problems may arise, for example, by cooling effects, by increasing the redox potential which in turn results in fermentation balance changes, and by partial flooding of extraction wells. Another serious problem that can result is the generation of increased volumes of leachate.

### *Leachate*

Landfill leachate is nothing but water that has percolated through emplaced refuse, with transportable organic and inorganic materials together with microorganisms such as bacteria and viruses. It is generated as a consequence of a complex of interacting factors which can be divided into first tier (site geology, hydrogeology, hydrometeorology, waste composition, refuse emplacement strategy, cover permeability, topography, vegetation cover and after-care, season and time) and second tier ($E_h$, pH, temperature, and physico-chemical reactions including acidification, volatilization, precipitation, solution, sorption, and ion exchange) factors [31]. The leachate coefficient of a landfill (C) may be described by the following equation:

$$C = \frac{Q}{10.I.A},$$

where Q is the leachate generation rate ($m^3$/day), I is the rainfall density (mm/day), and A is the surface area (ha) [34].

By 1990, more than 170 different individual chemicals had been identified in leachate from domestic refuse and co-disposal landfills [35]. If released, many of these will have damaging environmental impacts. Fortunately, by either natural attenuation (Class II sites) or specific treatment strategies, these impacts may be obviated.

Attenuation takes place through vertical and lateral movement and can occur in both saturated and unsaturated zones. In both instances, however, a critical factor is the rate of release of the initial flush of leachates, since high rates may exceed microbial enrichment rates particularly in the presence of xenobiotic molecules. A second factor is that migration rates and attenuation rates of different chemical species differ dramatically [36]. Finally, it must be recognized that partial degradation of individual constituents can result in the formation of more refractory compounds, low concentrations of which could migrate long distances to threaten groundwater [37]. To avoid this problem, the possibility of unsaturated zone seeding with microorganisms prior to starting refuse emplacement must increasingly be considered. The alternative is leachate collection and treatment. Such strategies can include *in situ* exploitation of the refuse mass and/or the use of external facilities, using the same principles as for industrial waste water [35].

*In situ* treatment involves the use of landfill as an anaerobic filter, where the leachate is recycled back through the refuse mass. The overall effect of this is to increase both the moisture content and its movement through the refuse which, in turn, promotes microbial catabolic processes (particularly if provision is made for pH control and/or nutrient supplementation by sewage sludge addition and/or microbial inoculation) and the physico-chemical mechanisms cited earlier. As an alternative to leachate recycle on site, soil application, by spray or surface irrigation, or sub-surface pipes or land drains may be used. In this case, the solid-state fermentation principles are essentially the same but may also include the effects of uptake by higher plants.

External treatments may be either by biological (aerobic and anaerobic) or by physico-chemical methods, and combined systems are often used to increase efficiency. Typical aerobic biological treatments include aeration lagoons, clay inclined planes, trickling filters, rotating biological contactors, and activated sludge units. Anaerobic treatment is usually carried out either in lagoons or in digesters, such as filters or upflow anaerobic sludge blanket plants. Physicochemical strategies, which have been applied to landfill leachate, include a whole range of treatments such as chemical coagulation and precipitation, carbon adsorption, reverse osmosis, resin adsorption, chemical oxidation, stripping and irradiation.

### *Inhibition of methanogenesis*

Landfill gas, with 80 or more known constituents, has not been recognized traditionally [38]. However, as the composition (especially the methane content) has changed with time, mainly through changes in refuse components and in site practice, it has increasingly been regarded as a liability or as an opportunity for energy recovery [28]. Today, the insidious environmental impact of the generated methane has been clearly recognized. Other problems associated with uncontrolled gas release include odour, the acidification of groundwater and reduced crop yields, including complete diebacks. Fortunately, these can be minimized by the use of cut-off barriers or trenches (to prevent lateral migration), gas extraction or air injection systems (on sites more than 6 m deep), and gas seals [39]. Once gas migration has been controlled, potential environmental impact problems may be minimized either by flaring off or soil sieving [38]. Of the two, flaring has a distinct advantage in that if the flame becomes extinguished, it invokes an immediate public response.

Control measures such as these, however, may be dispensed with by direct inhibition of methanogenesis in the refuse mass. Methanogenic species are particularly susceptible to the direct and indirect effects of environmental variables and specific refuse components (Figure 6) [5]. For example, competition with reductive deaminating, nitrate-reducing and sulphate-reducing bacteria for common precursors, particularly electron donors, may be regarded as one of the principal constraints on methane production. Thus, as discussed earlier, in the presence of electron acceptors such as nitrate and sulphate, sequential utilization (NO – > $SO_4^{-2}$ – > $HCO_3$ –) is apparent [21].

In addition to exogenous inorganic electron acceptors, such as the above, many other chemicals which challenge methanogenic activity may be present in refuse [5]. For example, chemicals such as chlorinated hydrocarbons and detergents are directly toxic as are heavy metals, though the presence or absence of chelating or precipitating anions and the prevailing pH must also be considered here. Together with refuse constituents, metabolic products can also exert direct and indirect effects. For example, an extremely low partial pressure of the hydrogen produced by fermentation must be maintained by interacting proton-reducing

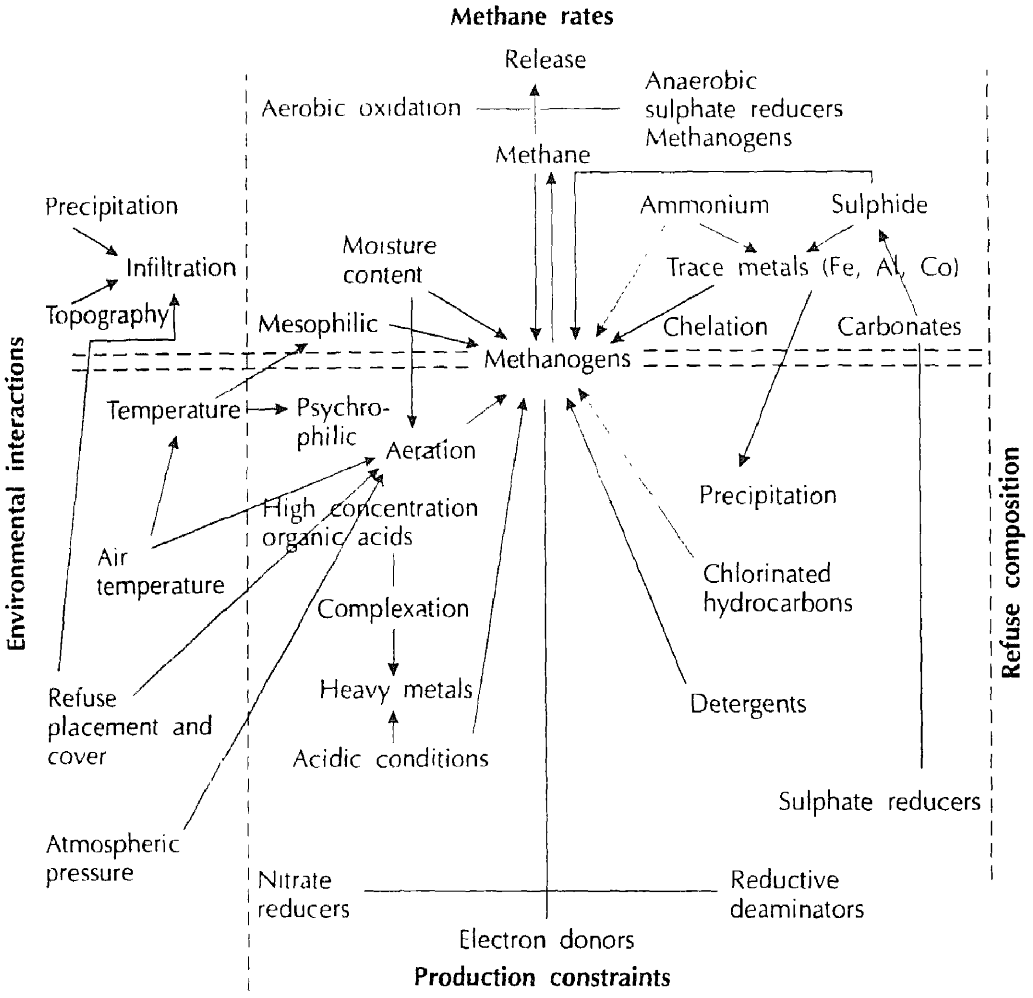


**FIGURE 6.** Methanogenesis—constraints in the landfill bioreactor.
*Source.* Senior E, Kasali G B. 1990. *Microbiology of Landfill Sites*, edited by E Senior. Boca Raton: CRC Press.

bacteria with obligate hydrogen-sink bacteria. This would facilitate favourable thermodynamic conditions and so prevent the accumulation of reduced organic acids (propionic, lactic, butyric, valeric, caproic), which themselves could prove inhibitory, through concentration and/or pH effects, to subsequent catabolic processes, particularly methanogenesis. If the hydrogen-sink is provided by sulphate reduction, then the production of un-ionized hydrogen sulphide at concentrations in excess of 50 mg/l poses a direct toxic threat to methanogens [40]. Even non-toxic concentrations of hydrogen sulphide may inhibit methanogens by precipitating essential trace metals, particularly nickel. Finally, although methanogens have an obligate requirement for ammonia, which may be facilitated by the formation of microbial associations of amino acid-degrading bacteria, concentrations of ammonia must be kept below a minimum inhibitory threshold of about 0.4 g/l [41].

Although inhibition of methanogenesis may be facilitated by each of the above mechanisms, perhaps the simplest approach would be the rapid elution of the refuse mass with either water or recycled leachate, which would result in the production of high concentrations of fatty acids. This, in turn, would lower the pH to the detriment of the methanogens. By manipulating leachate production in this way, consideration could also be given to the solubilization of the molecules such as lignocellulose by promotion of acid hydrolysis, which would reduce the current protracted stabilization periods and thus allow the land to be returned to positive use more quickly. This is particularly important in industrialized nations where available land is limited.

This approach, however, would result in the production of leachate with very high biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC) values. In a separate system, the selective treatment of such a leachate by anaerobic digestion could result in methane production approximating to the theoretical maximum, which would actually be a ten-fold improvement over most normal on-site recovery. Moreover, the methanogenic fermentation, being separated from the landfill treatment, could be controlled by loading rate adjustments and so could be made to match energy production with industrial demand, both in quality and in timing. This would be reflected in the digester configuration. Since leachate quality varies with time, a series of digesters would be required to mirror the size of the sites; but the number would be reduced when the concentration falls. This strategy would grab the advantage that the use of holding tanks for both leachate and gas would be minimized and the modular digesters could be moved from site to site as required. As an alternative, centralized digester could serve a number of sites although the cost of transporting leachate might prohibit this.

The attractiveness of using digester methane as a source of energy can be assessed by considering the increasing volumes of natural gas recovered by man, which is still rising exponentially.

Despite obvious attractions, methane generation from waste streams such as landfill leachate must be regarded as a short-term R & D objective as the product has a low market value per unit weight in comparison with other digester alternatives such as reduced organic chemicals and chemical feedstocks. Realization of such a selected product, however, would necessitate the channelling of carbon and electron flow by implementation of metabolic control mechanisms and/or genetic intervention, including the use of mutant strains.

## Temperature

Temperature-changes in landfill, which are relatively easy to measure but difficult to manipulate and control, are caused by a number of factors—both biotic and abiotic. The dominant biotic factor is microbial metabolism, which is itself directed by the emplaced refuse dry density, specific surface area, moisture content, refuse temperature, refuse composition and availability of electron acceptors, particularly oxygen, and to a lesser extent, by the intervention of a very miscellaneous but important population of invertebrates. Abiotic factors include chemical heats of neutralization and the absorption of solar energy. Energy generations or additions such as these are, however, balanced by heat losses to the atmosphere, to the surrounding soil, and to the emitted leachate [42].

Rapid increases in temperature are often indicators of aerobic microbial activity and this has prompted the use of temperature as an indicator of landfill behaviour. As discussed earlier, contrasting effects may then result in response to such temperature increases.

Temperature elevation is particularly important in landfill gas production since it has been shown that an increase in temperature (22–33 °C) can effect a 70% increase in gas production rate [43]. In a second laboratory study, temperature elevation from 18.7 °C (ambient) to 30 °C was shown to effect a 2.6-fold increase in the methanogenic rate; while a 7.8-fold increase was observed when the temperature was raised to 40 °C [44]. However, when the temperature was increased to 55 °C, there was a stoppage in the methanogenesis activity although solvent production was promoted. The results of this study also showed that at temperatures between ambient and 40 °C, refuse methanogenesis behaved almost in accordance with the Arrhenius model whereby reaction rates increase by a factor of between two and three for each 10 °C rise in temperature [45]. Surprisingly, increases in activation energy, indicative of slowing reactions, were also recorded. It suggested that within the mesophilic range, temperature was not the major rate limitation of methanogenesis.

Despite reports that landfill practices often mediate sub-optimal and wide temperature fluctuations in refuse, which result in unpredictable and low yielding methanogenic fermentations, it has been shown that at the Aveley (UK) Landfill, temperatures at depths greater than 3 m tended to deviate from the adiabatic and could be found to rise at a rate of 25 °C per year to reach 40 °C or more [46, 47]. A refuse placement strategy was also described by which a mesophilic temperature could be attained. The suggestion made was that initially, refuse should be placed at low density to promote aerobic catabolism and the temperature increase. The generated thermal energy would then heat subsequent layers of tipped refuse. There is, however, a danger of overheating which, in turn, could inhibit methanogenesis. Reports from Germany also advocated the use of an initial uncompacted aerobic layer for a period of six to nine months followed by second lifts of refuse supplemented with recycled leachate [48].

## pH/alkalinity

Manipulation of the pH regime in the refuse mass is particularly important in sites where *in situ* optimization of methanogenesis has been undertaken. It has been shown that an acetic acid to alkalinity ratio less than 0.8 is necessary to initiate the process [49]. However, in landfill sites, where the buffering capacity of refuse is high, for example, as a result of the addition of calcareous materials, methanogenesis will probably be initiated even in the presence of total concentrations of acid in excess of the limits reported in the literature [30]. Highest gas yields were attained with an alkalinity of 16 g calcium carbonate per kg total solids when stirred tank reactors were operated under anoxic conditions [50].

When the interrelated variables of pH and reduced organic acid concentration were examined, transient accumulation of acids (5 g/l) was recorded in conjunction with a pH of 5.4 [51]. The particular site was methanogenically active, however, within a period of two months, the pH progressively rose to 8.4 with a concomitant lowering of the fatty acid concentration to less than 0.02 g/l. Conversely, in *fresh* refuse, high initial fermentative activity can result in the accumulation of reduced organic acids and, thus, lower the pH to the detriment of the initially small methanogenic population. To obviate this possibility, single additions of exogenous buffer may be considered. The efficacy of 0.2 M phosphate buffer to promote refuse methanogenesis has been examined [52]. Gross pH values from neutral to alkaline were shown to promote acidogenesis to such an extent that methanogenesis was inhibited. Despite this inhibition, the results were particularly encouraging since they showed that pH manipulations could be used to facilitate carbon and electron flow of the solid-state fermentation to a selected group of products, such as solvents, and so exploit the reservoir of untapped potential of refuse.

Fermentation promotion by sodium bicarbonate supplementation has also been examined [53]. It has been shown that acidogenic-phase landfills are characterized by leachate bicarbonate concentrations of 17 mg/l in contrast with methanogenic-phase concentrations of 12 000 mg/l [54]. Buffering capacity was seen to increase by the addition of 2.5% (w/v) sodium bicarbonate, and promoted both acidogenesis and methanogenesis, with the latter accelerating by a factor of six compared with glass-distilled water controls. Increased bicarbonate concentrations (5% w/v), however, mediated partial suppression of methanogenesis and acidogenesis, possibly due to cation toxicity. The results of this study thus exemplified that extreme care must be taken in selecting the optimum concentration. Also, any improvements must be balanced against the significant cost factor of the alkali.

## Site seeding and nutrient supplementation

Present site inoculation takes place usually by chance with the invertebrate and microbial species, which are normally associated with the refuse. *In situ* enrichment of specialized populations may, thus, require protracted time periods. To avoid this, particularly for co-disposal sites, increasing considerations must be given to site seeding with specialized catabolic populations. Before inoculation of any such species into a site, however, the specific ecological constraints of the landfill must be considered, since the species must be the one which will proliferate under the particular environmental conditions. Selective advantage in a specific environment is linked with the growth of the introduced species on the targeted substrate. At low concentrations, it is essential that the mineralized molecule is converted to an increased population of the microbial cells. If not, the inoculated strains may not function in the ecosystem, because it is probably not feasible to introduce sufficient numbers of catabolically active cells to saturate the environment [55].

In addition, consideration should be given to the essential prerequisite of resistance to potentially toxic chemicals. It is also possible that in situations where the inoculated microorganisms are able to survive, the species may pick up plasmids carrying genes involved in detoxification but the plasmids may also be carrying genes coding for toxin production and other potentially detrimental traits.

## CO-DISPOSAL

Co-disposal is a low-cost operation in which industrial waste waters, solids, and sludges are disposed into emplaced refuse held in Class I or Class II landfill sites. In England and Wales, nearly 80% of the hazardous waste, total of more than 3.5 million tonnes per annum, is disposed in this way and the balance is accounted for by incineration, chemical treatment, sea disposal, mine-shaft disposal or solidification processes. Conversely, in Germany, Canada, and USA, this practice is discouraged or even outlawed due to the potential adverse environmental impacts and public concern arising from, for example, the notorious Love Canal incident. Even where co-disposal is permitted (in USA), the legislation demands that all new sites should be hired and have facilities for leachate collection.

In UK, where the practice of co-disposal has received official endorsements, three objectives have to be ultimately satisfied: (1) leachate quality must not be impaired; (2) the increased volumes of any liquid added must not pose added risk to ground or surface water; and (3) public opinion must be satisfied.

Co-disposal of industrial waste waters with refuse may be likened to treatment by downflow stationary fixed film reactors. Three methods—trenching, lagooning, and spraying—may be considered for application of the waste waters. Trenching, which is normally preferred, involves digging a trench, one excavator bucket wide and several metres deep in refuse, where there are at least 3 m of waste present below the trench bottom. When the trench is nearly full, it is back-filled with material from a parallel excavation.

Before initiation of co-disposal, consideration must be given to pertinent factors such as waste type (solid, sludge, liquid), the compatibility of reactive chemical species, the loading rate (hydraulic, organic), evaporation and transpiration rates, the leachability rate, and to refuse itself (type, quantity, density, and age) as well as to such overall factors as the site temperature and water balance [33, 56, 57]. In addition, a thorough understanding of the attentuation mechanisms operative for specific wastes and of the interdependent effects of landfill metabolism with the added xenobiotic(s) is essential. Until now, development of effective co-disposal strategies has been constrained by factors such as:

1. the wide range of industrial wastes disposed by landfilling (The contribution of domestic refuse is often overlooked. For example, in USA, each household annually contributes more than 5 l of hazardous waste);
2. lack of information on the possible hazards of mixing wastes in sites (here, segregation may have to be considered with preventive measures taken to minimize lateral movement);
3. a paucity of research on microbially-mediated degradative processes in refuse;
4. lack of consensus on the adoption of indicator parameters to monitor the fermentation [58].

Despite these, a balanced refuse fermentation does present physical, chemical, and biological mechanisms for the attenuation of both organic and inorganic components of industrial residues. Field data from the Pitsea Landfill (UK), where co-disposal was practised for more than 20 years, have shown no evidence of leachate hazardous waste constituents other than those present in typical leachate from stabilized refuse [59].

Despite the range of attenuation mechanisms operative within a refuse mass, very little data are available on these. By use of laboratory models, co-disposal of barium-containing salts with refuse has been examined and the importance of physico-chemical processes, particularly adsorption, exemplified [60]. Microbial activity was also implicated indirectly, since microbially-produced carbon dioxide and bicarbonate resulted in the precipitation of barium carbonate. The presence of fatty acids effected significant mobilization as organic complexes. Although microbiological transformations of radioactive wastes may be operative, it has been demonstrated that the co-disposal of radionuclides such as $^{3}$H, $^{58}$Co, $^{85}$Sr, and $^{134}$Cs again resulted in only indirect microbial intervention [61, 62]. Strontium and cobalt removals were attributed to sulphide and basic carbonate precipitation, while caesium concentration reductions were attributed to ion exchange with the solid refuse. Direct microbial involvement has, however, been observed in the co-disposal of soluble arsenical when, under strongly reducing conditions at neutral pH, reduction and methylation to di- and tri-methylarsine resulted [63].

In addition to these specific mechanisms, refuse age must also be considered. *Fresh* refuse exhibits both greater absorptive and buffering capacities than does *aged* refuse. Sulphate, chloride, and iron are only poorly attenuated when rapid liquid additions are made to low density material and, as a consequence, it has been advocated that liquid disposal should be made to old completed areas of sites with the added advantage of simpler leachate control [64, 65].

Although a site-specific maximum loading rate can be defined in relation to a known weight of refuse (at which no inhibition of microbial catabolic processes results, and therefore there is no impairment of leachate quality), quantified rates are very seldom available. Where quantified rates exist, they seem to have been derived simply from past practices which appear to have caused no problems. Two components may be considered with respect to loading rate—the organic loading and the hydraulic loading. For the organic loading rate concentration is critical and should be determined under environmentally relevant conditions to obviate potentially detrimental effects of shock loading. Since the hydraulic load of refuse is increased by co-disposal practices, particularly in the presence of leachate recycle, addition of large volumes of liquid to the surface of a site is likely to result in a degree of ponding or to perched water tables within a landfill [66]. In addition, rapid infiltration may adversely affect the refuse fermentation due to cooling and oxygen ingression.

Detailed laboratory studies of the co-disposal of phenol with domestic refuse have been made and have shown that the toxic effects of the molecule can be obviated by applying low concentrations in conjunction with elevated hydraulic loading rates [57, 67]. Although maximum dissimilation rates can be attained by such manipulations, the difficulty is to achieve high hydraulic loading rates *in situ*. When other factors such as perfusion strategies, the roles of different refuse fractions and refuse age, and the impacts on refuse catabolism were examined, it was shown that added phenol effected differential inhibition of the interacting microbial species [68]. Competition for common electron donors was thus eliminated thereby promoting methanogenesis. It was therefore apparent that realistic guidelines and strategies will only result from an understanding of the fundamental microbiology and biochemistry of co-disposal derived from environmentally relevant model studies [69].

Generally, the addition of xenobiotic molecules, which may be either directly toxic or may be converted to toxic products, leads to a decrease in the diversity of the microbial population as a result of species elimination or the enrichment of particularly successful population. Selective toxicity effects can sometimes eliminate a dominant organism leading to an increase in diversity. The concentration of a specific molecule can be critical since microbial degradation at a low concentration may utilize a different degradative pathway than occurs with the same compound at high concentration. Some of the most recalcitrant molecules are particularly persistent at low concentrations, and extremely low *in situ* concentrations may not be dissimilated at all though they may still constitute a biohazard. In general, for most organic molecules, the optimum concentration to sustain microbial growth is found in the range of 100–1000 mg/l. When these molecules are also toxic, their toxicity effects may be significant at far lower concentrations once they are released into wider ecosystems [55].

The options available for the treatment of leachate from co-disposal sites are essentially the same as those for municipal refuse leachate; consideration may well have to be given to the provision of specific inocula. However, it has been reported that interacting microbial associations, capable of catabolizing industrial landfill leachate, have been enriched and isolated from soil and sewage sludge for use in land-based biological and closed culture treatments, respectively, and more work of this kind is expected in the future [70, 71].

## SITE MONITORING

### Leachate

Results of leachate analyses may be used to assess potential environmental impacts and/or the stage of the solid-state fermentation [54]. Typically, a series of boreholes for sampling aqueous strata at different depths is sunk in the direction of the aquifer [37]. The boreholes may be lined with PVC or the more expensive well screen, and should be effectively capped. Top terminations should always be above ground level to prevent contamination from spillage and run-off. As an alternative to these simple structures, more sophisticated pressure vacuum lysimeters may be employed [72]. The physical disturbance of drilling may upset the natural flow in the aquifer and induce vertical flow in the borehole thus complicating chemical assay result interpretation. To overcome these problems, several boreholes of different depths may be required or, alternatively, small diameter piezometer tubes may be installed at different discrete positions in a larger diameter borehole [73].

A decade ago, a detailed study of groundwater pollution monitoring was carried out and it was concluded that the number and locations of boreholes, the frequency and method of sampling, the parameters for analysis and the methods of analysis should be determined only after consultation with the local statutory authority [74]. For routine analysis, it was suggested that chemical assay could be limited to chloride, sulphate, and organic carbon provided that more detailed analyses would be made if a pollution plume was detected. The need for both surface and groundwater analyses and for complementary regular analyses of ground permeability by either pumping or falling head tests was also stressed. Finally, basic interpretations of leachate parameters were made, which are as follows: (1) high ammonia indicated close proximity to landfill site and anaerobic degradation in progress; (2) absence of ammonia and presence of nitrate indicated distance from the site and aerobic conditions; and (3) presence of chloride above background concentrations indicated presence of leachate which, together with ammonia and organic matter, indicates leachate not fully degraded.

### Gas

For both economic and environmental impact considerations, effective monitoring of landfill gas emission has become increasingly important. To achieve this objective, boreholes must be sunk into the sites so that representative gas samples may be collected for analysis. Detailed descriptions of borehole/probe configurations have been made [75]. After examination of various probe types, a number of variables for consideration in the development of a comprehensive sampling programme have been identified [76]. Principal among these are probe depth, distance between probes, atmospheric conditions, and the time interval between samples. From this study, it has been concluded that due to potential variability of gas migration rates, a routine gas monitoring strategy should differ significantly from a groundwater monitoring strategy, particularly in terms of sampling frequency.

Gas monitoring programmes involving boreholes have been used to estimate the methane generation rates prior to gas abstraction. However, accurate rates are difficult to obtain since gas collection techniques can change *in situ* conditions quite dramatically. One method described involves pumping gas from a well sunk in the landfill and then determines the sphere of influence by monitoring pressures within the refuse mass [31]. Unfortunately, such a method, at best, can give only an estimate of gas release and not of production. A more valid method would be to use radiotracer techniques with due consideration to chemical species pool sizes, chemical equilibria, and extraction efficiencies of the specific precursor involved.

## FUTURE DEVELOPMENTS

Despite growing public concern, it has been proved that the method is both safe and reliable even with the challenge of an increasingly unfavourable demographic distribution, provided adequate care is taken with site selection and preparations. Further, without this cheap disposal option, the environment would become increasingly vulnerable to the possibility of illicit uncontrolled tipping.

During the last decade, much emphasis was placed on landfill research, particularly with respect to civil engineering aspects. In spite of this attention, surprisingly, little definitive microbiology and biochemistry has yet emerged. Our knowledge of how to control and exploit the solid-state fermentation within the landfill bioreactor is still extremely limited, and it is perhaps time to increase our efforts if the genuine needs of the landfill industry are to be rightly satisfied. Armed with such knowledge, scientific management may be introduced which, in turn, would help to allay public fears and thus restore confidence in this previously trusted practice.

As discussed earlier, fermentation control is dependent on a complete understanding of the complex interspecies interactions—the waste biotechnology engine.

## Classification of interspecies interactions

Classification of interspecies interactions has been problematic and the schemes already proposed have yet to get universal acceptance. For convenience alone, classification schemes may be divided into two broad groups—classical and contemporary. The classical approach attempts to describe interactions by use of zoological labels while the contemporary approach considers microbial associations on the basis of structure [77, 78].

Two species associations, with their nine possible interspecies interactions, may be effectively described by use of classical labels—neutralism, competition, amensalism, predation, mutualism (symbiosis, protocooperation, synergism, syntrophism), commensalism, and parasitism (Figure 7) [79]. Problems do exist

| | | **Effects of Species A on Species B** | | |
|---|---|---|---|---|
| | | 0 | + | – |
| **Effects of Species B on Species A** | 0 | 00 | 0 + | 0 – |
| | + | + 0 | + + | + – |
| | – | – 0 | – + | – – |

**FIGURE 7.** Interspecies interactions of a two-membered microbial association. *Source.* Bull A T. 1985. Mixed culture and mixed substrates systems. *Comprehensive Biotechnology. Volume I. The Principles of Biotechnology: Scientific Fundamentals,* edited by A T Bull and H Dalton. Oxford: Pergamon Press.

when the operative relationship can be described by more than one label and when changes result in response to first- and second-tier environmental variable perturbation(s). Similarly, when an association is constituted by many species, descriptive characterization of the concomitant interactions is particularly difficult.

To get over these potential problems, microbial association classification on the basis of structure may be considered [78]. In this approach, structure may be attributed to seven possible factors as given below.

1. The provision of specific nutrient between different members of the community.
2. The removal of potentially inhibitory metabolic products.
3. The interaction resulting in modification of individual population growth parameters, resulting in increased competitiveness or efficiency of the community.
4. The emergence of metabolic capability not expressed by individual components.
5. Co-oxidation (co-metabolism).
6. Interspecies hydrogen transfer.
7. The presence of more than one primary substrate utilizer.

Characterization of interacting microbial associations by any of the above approaches does, however, necessitate determination of the bases of the interactions.

## The solution

The clear solution to the problem is the use of realistic models, which are maintained under defined and controlled conditions [69]. Development of such models does, however, necessitate a clear definition to the problem under study as an essential prerequisite.

Traditionally, the challenge of model development has been ignored and interacting associations have been studied either as single entities or, alternatively, by following a reductionist approach. In the reductionist approach, monoculture isolates have been examined singly or in dual or in triple culture. The former approach produces only meaningful data of the key interactions, while the latter is invalid since the constraints of the interacting associations have been violated. A more realistic approach is a combination of the two in which the organisms are studied in isolation (exclusive habitat domains) but within the constraints of the association (overlapping activity domains) (Figure 8; see next page).

## Methods of study

The homogeneous chemostat, operating under *steady-state* conditions, has often been the model of choice. Despite their limitations, single-stage chemostat models

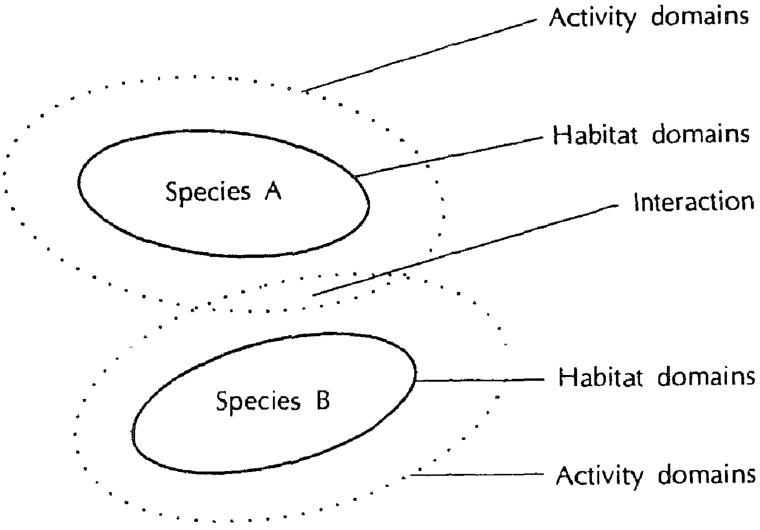


**FIGURE 8.** Interspecies interaction in a dual culture.

may be used to examine phenomena such as metabolic communication amongbiodegradative populations and biochemical cycling of organic matter, competitive displacement, overlapping niches, selection and evolution of microorganisms subjected to substrate selection pressure, solute diffusion across the oxic–anoxic interface, effects of physiological determinant perturbations on microbial integrity, and control mechanism correlations [80]. The models, unfortunately, have little value in studies involving either mutually exclusive niches such as nitrate reduction and methanogenesis or niches with limited overlap.

Linked homogeneous chemostats do not, however, suffer from these limitations since interactions between microorganisms can be examined provided their activity domains overlap. Without these essential overlaps, interactions will not occur at significant rates. Multi-stage laboratory models can be used to study sequential catabolism (where the spectrum of physiological types is spatially arranged through each discrete vessel) [81], sequential use of electron acceptors and simultaneous use in overlapping niches [82], mixotrophy, generation of nutrient gradients [83], microbial competition [84], synergism and antagonism [23], appearance of emergent properties [85], maintenance of species diversity (particularly specialists) [82], and interfaces [84]. As a consequence, both process description and demonstration of species diversity can be made simultaneously.

A linked homogeneous chemostat array offers a more valid model than does a single-stage system to study the metabolic processes of refuse catabolism. However, limitations are yet to be recognized. Multi-stage chemostats produce stepped changes in solute concentration rather than true gradients and, as a consequence, spatial resolution is limited to the number of individual vessels [79, 83]. The important factor of surface, which is extremely difficult to model, is essentially absent and thus the growth rate-dependent (free-living) organisms are transferred from vessel to vessel [83, 86]. Finally, unless careful consideration is given to the surface area to volume ratio, considerable artefactual errors may result.

Multi-stage chemostats may be operated under unidirectional flow or bidirectional flow [80, 83]. In the case of the former, the model washes out sequentially, while the system as a whole has approximately the same residence time as a single vessel of the same volume. However, the slow-growing species can be retained by progressively increasing the volumes (thus decreasing the dilution rates) of the individual vessels down the array (Figure 9; see next page) [81]. This species maintenance is particularly important in studies of sequential metabolism which is dependent on a series of separate transformations, which individually do little to benefit the participating organisms [87].

Additionally, both commensal and competitive populations may be monitored within the same system thus facilitating, for example, studies of the pivotal role of the exogenous electron acceptor sulphate. Like single-stage chemostats, multi-stage models can be operated with careful control of second-tier environmental variables such as pH, $E_h$, and temperature or, alternatively they may be allowed to self-generate redox, and/or pH gradients. By careful influent control of available electron donors and acceptors, small changes, which can significantly alter both the particular population and the metabolic control between the specific trophic groups, may be made as a prerequisite to fermentation optimization [84].

Multi-stage chemostat models are powerful tools for making definitive studies of the fundamental interactions operative in the refuse mass. Such models may be used to:

- identify rate-limiting steps of refuse catabolism as a prerequisite for physiological optimization of key species;
- examine fermentation balance and species changes (including displacement) in response to organic shock loads and hydraulic load changes (during co-disposal operation);
- identify key species for physiological/genetic manipulation;
- examine fermentation balance and species changes in response to quantitative and qualitative changes in electron acceptors;
- examine species response to environmental variable perturbations, such as pH and temperature change;
- describe interspecies interactions;
- identify interfaces; and
- construct predictive models.

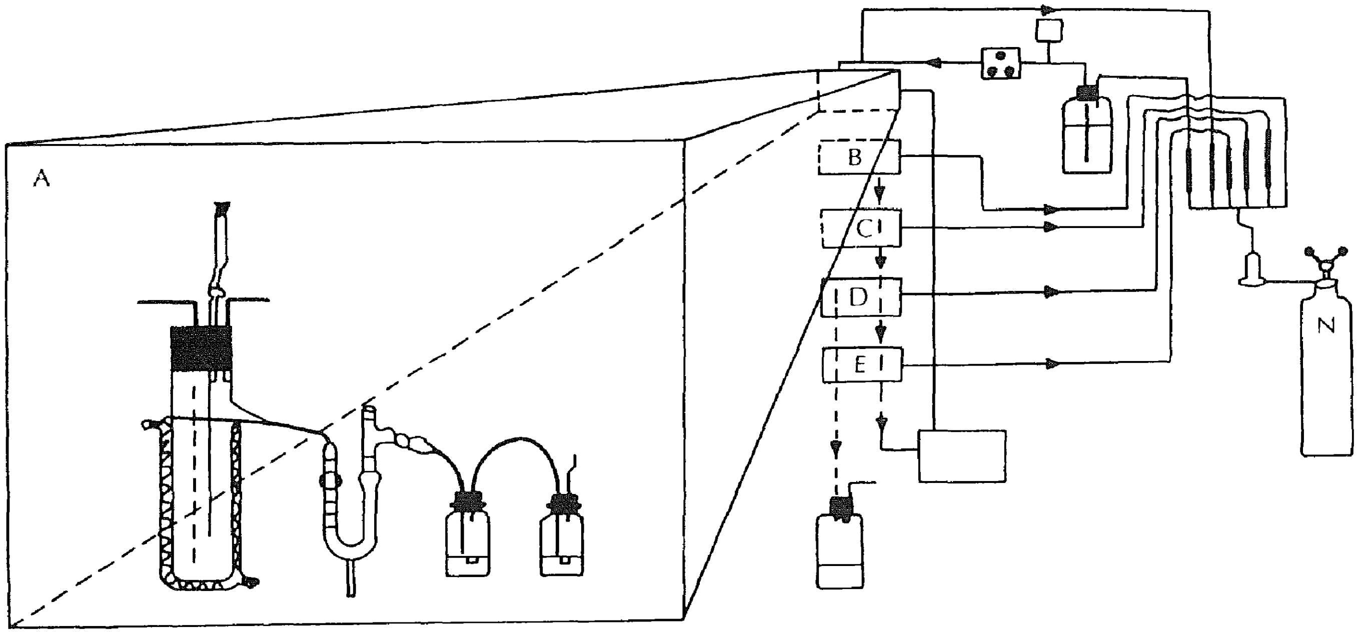


**FIGURE 9.** Multi-stage chemostat model consisting of five identical vessels (inset), A–E, arranged vertically.
*Source* Coutts D A P, Senior E, Balba M T M. 1987. *Journal of Applied Bacteriology* **62**: 251–260.
]

## CONCLUSION

It has taken many man-years to develop laboratory models, which are so essential for fundamental definitive studies on waste biotechnologies such as landfill. Armed with such models and with so many problems clearly identified, quantum leaps in the treatment or exploitation of all waste streams, and thereby protecting the environment should be anticipated. However, skilled manpower, which is a global problem, is needed at all levels, i.e., from operator/technician through management and on to researcher. For that, proper training should be given to waste technologists. Adequate funding from government as well as industry is also very essential. Any perceived or real recession must not be used as an excuse to avoid this responsibility. This is one investment which we cannot afford not to make. If we do, then we will be rightly reviled by future generations as the generation which, given temporary custody of this globe, not only totally abrogated on its responsibilities to protect and improve the biosphere but also irreparably vandalized the planet.

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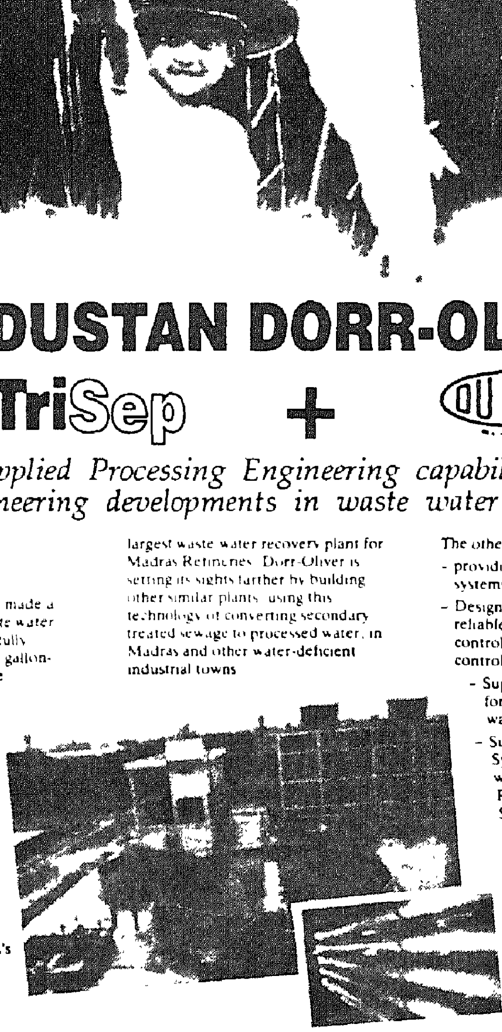

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## 10

# Municipal waste water treatment and energy recovery

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## INTRODUCTION

In India, waste water treatment has achieved great significance specially after the formulation of the Ganga Action Plan (GAP). Prior to this, only large cities like Delhi and Bombay had waste water treatment facilities. Since the scale of waste water treatment schemes is large under GAP, Yamuna Action Plan (YAP), National River Action Plan (NRAP), and the various other projects of the state level urban bodies, choice of appropriate technologies for waste water treatment and their technical and financial viability become important issues. In this context, resource recovery, savings in energy, and energy production in the form of biogas have gained high priority in order to have low operation and maintenance (O & M) costs.

Of the many technologies available, upflow anaerobic sludge blanket (UASB) technology for waste water treatment has emerged as an important technology option after the success of the various schemes of GAP in Kanpur and Mirzapur under the Indo–Dutch project. Based on the positive evaluation by the joint mission of experts from the Government of India and the Netherlands, the Ganga Project Directorate (GPD) is introducing UASB technology for waste water treatment in cities under YAP and NRAP, wherever biological treatment is the chosen option. Behind this choice, savings in investment and O & M costs, and options for reduced energy consumption and energy recovery have been the major factors considered.

This paper deals with municipal waste water treatment and energy recovery, and proposes a strategy for sustainable urban waste water management with special reference to UASB technology and energy recovery. It also discusses the experience of consultants with respect to waste water treatment and other allied components. The data used mainly relate to the Indo–Dutch Environmental and Sanitary Engineering Project in Kanpur and Mirzapur under GAP in which IRAMconsult is providing their services along with HASKONING, Royal Dutch

Consulting Engineers and Architects within the bilateral co-operation framework of the governments of India and the Netherlands.

A study conducted by the Central Pollution Control Board on the status of water supply, waste water collection, treatment, and disposal had the following to say regarding the position in 10 metro cities [1]. About 93% of metro population is covered by organized water supply. Contributions of water supply from surface and ground sources are 87 and 13%, respectively. The water supply varies from 76 litres per capita per day (lpcd) in Madras to 307 lpcd in Kanpur, with the metro average of 189 lpcd being higher than the national average of 147 lpcd for 212 Class I cities. About 6462 million litres per day (mld) of waste water is generated from the 12 metros, which is 53% of the total waste water generated from the 212 Class I cities. Twenty-seven million people are covered by sewage facilities in the nine cities, which provided information about its coverage.

In the top 10 Indian metros, 11 665 mld waste water is expected to be generated by 2001, of which 6045 mld will be treated, neglecting the rest, assuming that the present trends of waste water generation and increase in treatment capacity levels will continue [2]. The selection of treatment technology, taking into account the cost factor also, is extremely important.

Freshwater sources for municipal consumption and agriculture are fast running out. Besides improving efficiency, another way to stretch freshwater supplies is to recycle and reuse treated municipal waste water for irrigation and other purposes. By using municipal water twice, i.e., for domestic use and later for irrigation, the pollutants would become valuable fertilizers. Thus, rivers and lakes are protected from contamination, the irrigated land boosts crop production, and the reclaimed water becomes a reliable, local supply.

At least 500 000 ha of cropland in some 15 countries are now being irrigated with treated municipal waste water. Israel has the most ambitious waste water reuse programme in the world. Already some 70% of the nation's sewage gets treated and reused to irrigate 19 000 ha of agricultural land. With no new sources of freshwater to tap, Israel plans to expand the use of reclaimed waste water greatly by the end of the decade. Virtually, it has been projected that freshwater allocation to agriculture will be reduced by 38% by the year 2000 compared to what it received in 1984 [3].

## THE GANGA ACTION PLAN

The Ganga river extends 2525 km from the Himalayas into the Bay of Bengal, providing shelter to about 37% of India's population (242 million) in its basin. Roughly 100 cities with a combined population of 15 million discharge liquid and solid waste into the river, usually with no prior treatment, causing (i) pollution of river water beyond the river's regenerative capacity, (ii) contamination of vegetables and infection of farm workers from untreated sewage dumped onto farmland, and (iii) health hazards to millions of pilgrims who visit the Ganga and bathe in its waters.

The Central Government, with assistance from Uttar Pradesh Government, established the Central Ganga Authority (CGA) in 1985 to develop a plan for preventing pollution. The CGA is chaired by the Prime Minister of India. The Ganga Action Project Directorate, headed by a senior civil servant, will be responsible for the implementation of the plan [4].

The GAP applied a least-cost calculus to a number of key issues in water quality. The fundamental one is the balance among standards, costs, and coverage. A model is used to calculate the degree of pollution that the river can accommodate at various points and to incorporate this information into effluent standards. In general, GAP focuses on primary treatment on a very large scale as it is more cost-effective than small-scale, secondary, and tertiary treatments.

The various sewage treatment alternatives also must be examined. Technical characteristics, as well as the availability of land in cities where treatment plants are to be located (Allahabad, Haridwar, Varanasi, Mirzapur, and Kanpur) have to be considered while making the choice. There is a large demand for sewage to fertilize farmland, and GAP expects substantial recovery of O & M costs from this market. Finally, cost-effective programmes require that adequate data be available promptly to decision makers.

Accordingly, the following components have been identified for the Action Plan.

- Renovation (cleaning/desilting/repairing) of existing trunk sewers and outfalls to prevent the outflow of sewage into the Ganga.
- Construction of interceptors to divert flow of sewage and other liquid wastes away from the Ganga.
- Renovation of existing sewage pumping stations and treatment plants, and installation of new sewage treatment plants to recover maximum possible resources.
- Providing sullage or sewage pumping stations at the outfall points of open drains, to divert the discharge from the river into the nearest sewers and treatment plants.
- Monitoring of gross polluting industries located on the Ganga and taking necessary steps to reduce water pollution by such units.
- Low-cost sanitation schemes in areas adjoining the river to reduce or prevent the flow of human wastes into the river.

- Construction of electric crematoria along the river bank for cremation of dead bodies to prevent throwing of partially burnt or unburnt bodies into the river. The use of electric crematoria will also save considerable amount of firewood.
- Development of bathing ghats along the river at selected locations so that the river front is maintained clean.
- Biological conservation measures based on proven techniques for purification of streams.
- Pilot projects to establish cost-effective system for diversion of wastes now flowing into the river, their treatment, and resource recovery.
- Pilot projects to establish the feasibility of technological innovations in the treatment of wastes and resources/energy recovery [5].

The pollution control programme in the Ganga involves many organizations such as local bodies, industrial units, state and central agencies, specialist organizations, expert groups, and so on. Above all, public co-operation and participation have to be mobilized to sustain awareness about the problems of river pollution, to speedily implement the action plan and to maintain the purity of the river.

## INDO–DUTCH ENVIRONMENTAL PROJECT

The Indo–Dutch Environmental and Sanitary Engineering Project at Kanpur and Mirzapur, under GAP, follows an integrated approach for tackling the problems of domestic and tannery waste. Besides prevention of pollution of River Ganga, the other major objective is to improve the environmental and living conditions of the people of Jajmau, the industrial area of Kanpur with a large cluster of tanneries, and Mirzapur. Under this project, 11 schemes in Kanpur and nine schemes in Mirzapur have been implemented with a total financial assistance of 50 million Dutch Guilders. The project, started in June 1987, was completed by June 1994, except for an add on component (post-treatment plant) at Kanpur. The main objectives of the project are:

- to develop integrated delivery systems for sewage, stormwater, drainage, water supply, low-cost sanitation, treatment of domestic and industrial (tannery) waste water, collection and disposal of solid waste, and public health education utilizing effective community participation with an aim not only to control the pollution on the river Ganga, but also to improve the general environmental and living conditions of the target population in Jajmau, Kanpur, and Mirzapur;
- to demonstrate the application of such an Integrated Approach in Jajmau, an area which is characterized by a mixed industrial and residential use within

the city of Kanpur and to develop basic criteria for technical design in sanitary engineering projects for combined treatment of domestic and industrial waste water;

- to demonstrate the application of such an Integrated Approach in a medium-sized city of Mirzapur and to develop basic criteria for technical design in sanitary engineering projects for treatment of domestic waste water; and
- to demonstrate the usefulness of anaerobic waste water treatment process.

In Kanpur, a number of interventions have been made to tackle the environmental problems of a large cluster of tanneries in Jajmau area. These include interception and conveyance of tannery and municipal waste water, UASB treatment of combined tannery and municipal waste water, water supply, low-cost sanitation, stormwater, drainage, chrome recovery and reuse, tannery solid waste and municipal waste management, and public health and occupational health aspects of tannery workers in conjunction with community participation. In Mirzapur, the project interventions cover UASB treatment of municipal waste water, sewerage and stormwater drainage systems, low-cost sanitation, water supply and solid waste management, and community participation and health aspects. Institutional development and training activities have also been undertaken.

The various project schemes, which have been implemented in Kanpur and Mirzapur, along with their respective investment costs as well as their responsible implementing and O & M agencies are given in Tables 1 and 2 (see next page) [5].

While formulating environmental protection measures for the tannery industry in Jajmau, the tannery owners, the tannery workers, the branch organization of the industry and leather research institute, the government agencies for project implementation, regulation and control of pollution, donors (Dutch Government), central and state government officials, and the consultants have all worked in good coordination and all facets of the problems have been taken into consideration.

The implementing agencies for GAP and the Indo–Dutch project belong to the Uttar Pradesh Government. Coordination and implementation of the policy are performed by the Ganga Project Directorate at the Central Government level. For the Indo–Dutch project, a consortium of consultants comprising HASKONING and EUROconsult from the Netherlands and IRAMconsult and Associated Industrial Consultants (AIC) from India was appointed to render advice on design and implementation of the project. They played a key role in fulfilling the objectives of the Kanpur–Mirzapur project. They supplemented the local technical and institutional expertise and facilitated the introduction of new technologies like the UASB process. Moreover, the concept of the Integrated Approach was introduced on their initiative.

**Table 1.** Project schemes in Kanpur

| Project scheme | Implementing agency | O & M agency | Investment cost (Rs in millions) |
|---|---|---|---|
| Industrial waste water conveyance system | UPJN[1] | UPJN | 42.968 |
| Expansion of domestic sewerage system | UPJN | KJS[2] | 27 496 |
| Stormwater drainage system (Phase I + II + III) | UPJN | KNM[3] | 25.864 |
| Repair and cleaning of sewers | UPJN | KJS | 3.418 |
| 5 mld UASB treatment plant | UPJN | UPJN | 10 016 |
| 36 mld UASB treatment plant | UPJN | UPJN | 118.814 |
| 36 mld post-treatment plant | UPJN | UPJN | 57.477 |
| Low-cost sanitation | KNM | KNM | 27.752 |
| Water supply | UPJN | KJS | 27.786 |
| Solid waste management | KNM | KNM | 8.722 |
| Community participation and public health aspects | KNM | KNM | 3.995 |
| Chrome recovery pilot plant | UPJN | —[4] | 0.273 |
| 10 m$^3$ pilot plant for tannery waste water | UPJN | —[4] | 1.113 |
| GRAND TOTAL | | | 355.694 |

[1] Uttar Pradesh Jal Nigam; [2] Kanpur Jal Sansthan; [3] Kanpur Nagar Mahapalika; [4] These were only meant for pilot-scale studies and are not maintained now.

*Source.* HASKONING, EUROconsult, IRAMconsult, AIC. 1992. *Integrated Approach and Replicability*, Draft report Nijmegen, The Netherlands: HASKONING.

**Table 2.** Project schemes in Mirzapur

| Project scheme | Implementing agency | O & M agency | Investment cost (Rs in millions) |
|---|---|---|---|
| Crash programmes sewerage and stormwater drainage | UPJN | MNP | 3.324 |
| Interceptor sewer and pumping stations | UPJN | UPJN | 37.610 |
| Wide meshed sewage system in the core area | UPJN | UPJN | 33.995 |
| Expansion of drainage system in non-core area | UPJN | KNM | 37.127 |
| 14 mld UASB treatment plant | UPJN | UPJN | 37.624 |
| Low-cost sanitation | UPJN | MNP | 27 752 |
| Water supply Phase-IB | UPJN | MNP | 18.592 |
| Solid waste management | MNP | MNP | 2.392 |
| Community participation and public health aspects | MNP | MNP | 3 912 |
| GRAND TOTAL | | | 202.328 |

*Source* Same as in Table 1

## INTEGRATED APPROACH

Integration refers to interrelationships among technical components such as sewage treatment, sewerage and stormwater drainage, water supply, sanitation, and solid waste management. It also refers to the integration of the technical distribution systems with the socio-economic, cultural, and institutional set-ups at the municipal and community level.

The broad policy guidelines for an Integrated Approach identified by the project experience so far are as follows.

- Need for identification of programme-specific objectives and interrelated components to formulate projects for realizing an Integrated and Sustainable Approach.
- Need for adopting a budgetary formula of classified credit lines for various programmed objectives rather than rigid allocations for pre-identified project activities. This should help in realizing a dynamic approach in planning and implementation of the project activities.
- Incorporating a number of potential elements of technology with proven success, namely, UASB process and chrome recovery/reuse; systematic engineering approaches, namely, crash programmes, social profiles as a base for deciding the nature of engineering services; and institutional development in terms of training and techniques-support.

## UASB SYSTEM—A CLEAN TECHNOLOGY

The USAB process was developed at the Agricultural University in Wageningen, the Netherlands and has already been applied for treatment of a large variety of waste waters. Presently, over 150 full-scale plants are in operation worldwide for the treatment of both domestic and industrial waste waters. In India, for domestic waste water treatment, the UASB technology has been further developed to suit local conditions. The biogas production, low energy consumption, and high loading rates are important features of this system. The UASB process is depicted diagrammatically in Figure 1 (see next page).

In a UASB reactor, the treatment tank consists of an upflow reactor with a feed inlet distribution system at the bottom of the reactor and a gas–solids–liquid (three phase) separator at the top. The waste water is evenly distributed over the reactor-bottom through feed inlet pipes, and flows upwards through a bed of anaerobic sludge in the lower part of the reactor called the digestion compartment. During passage through the sludge bed, particulate matter is entrapped and the degradable matter is completely or partially digested. Dissolved organic matter is removed from the solution by the anaerobic bacteria and converted into

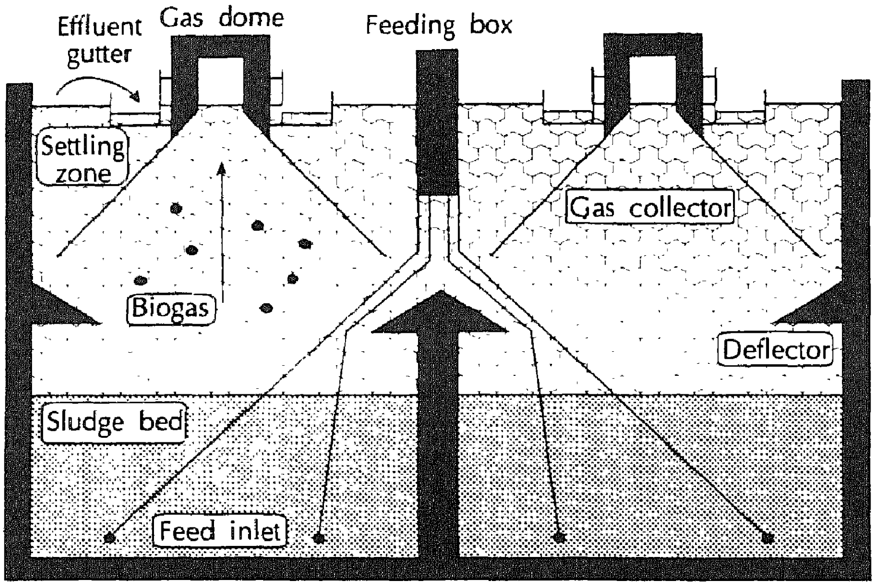

FIGURE 1. UASB process.

biogas and a small fraction into new bacterial biomass. The biogas provides a gentle mixing in the sludge bed. The biogas produced is collected in a gas collector (gas hood) from where it is withdrawn. The remaining water–sludge mixture enters a settling compartment where the sludge can settle and flow back into the digestion compartment. After settling, the water is collected in effluent gutters and discharged out of the reactor. The salient features of the system are:

- low energy consumption;
- generation of methane-rich biogas (75–80%);
- low surplus sludge production;
- achievement of about 75% COD, 80% BOD, and 80% TSS removal; and
- retention of nitrogen (N), phosphorus (P), and potassium (K) in the sludge.

## Advantages of UASB over traditional aerobic processes

1. A UASB treatment plant has fewer mechanical components, thus saving O & M costs as well as eliminating problems that may arise after the breakdown of a high maintenance intensive process.
2. Due to its simple nature, the energy requirements of a UASB reactor are very low. At the same time, it produces energy in the form of biogas, which is rich in methane and has a high calorific value. The biogas generated can be used

for the production of electricity, which can meet the power requirement of the UASB plant. If gas production and collection are properly controlled, considerable amount of energy can be saved even after the plant requirements.

3. Retention of active sludge is one of the most important features of the UASB process. Because of this, very high loading rates are possible and a high sludge retention time is achieved. The reactor can be started up with ease even after the plant is shut down for months. Therefore, the process is very good for treating waste waters from seasonal industries as well. In aerobic treatment plants, power failures will result in sludge settling. The sludge has to be resuspended after power failure. In case of prolonged power failures (longer than six hours), the aerobic sludge undergoes digestion anaerobically and produces bad odours. With very long power failure, aerobic process has to be restarted completely. On the contrary, a UASB system is less sensitive to interruptions in the waste water supply. After power breakdowns, the process starts immediately and no specific operations are to be executed. In developing countries, power failures are quite frequent and hence a UASB system is more appropriate and cost-effective as compared to an aerobic system.
4. UASB systems require less space. This is a big advantage considering the pace at which our cities are developing.
5. If very strict standards for the quality of effluent are not to be achieved, the cost of a UASB plant would be significantly lower than that of an aerobic plant. However, if strict standards are to be met and a post-treatment is required to follow the UASB process, the margin will reduce, but the cost of UASB + post-treatment combination would still be lower than that of a purely aerobic system.
6. The production of excess sludge in a UASB reactor is very low. This reduces the load on the sludge treatment system. Further, the sludge from a UASB reactor is highly stable and has very good dewatering and drying characteristics. Since N, P, and K are retained in the sludge, it has a good fertilizer value.

## Technical aspects

Being a technology based on microbiological degradation of organics in waste water, the treatment plant performance will be sensitive to temperature, pH, hydraulic gradient, and design parameters. Therefore, it is necessary that for designing UASB plants experts should be involved. UASB treatment plants can be built in any size. Generally, cost gets reduced as the size of the plant increases.

### *Energy recovery from municipal sewage*

The biogas produced by a UASB reactor operating on domestic/municipal sewage has the following average composition.

$CH_4$—75–80%
$CO_2$—5–10%
$N_2$—15–20%
$H_2S$—<1%

The production of biogas from domestic waste water can be estimated at 0.15–0.25 $m^3$/kg $COD_{rem}$. This is equivalent to 10–15 l of biogas per p.e. per day. The biogas yield, 0.15 $m^3$/kg $COD_{rem}$, at the 5 mld UASB treatment plant at Kanpur enables a biogas production of 150 $m^3$/day (Table 3) [6].

In large plants, gas utilization becomes feasible for heating or energy production, thus making the plant independent of external energy supply. The energy value of biogas containing 75% methane can be illustrated by the following composition. Theoretically, one cubic metre of biogas is equivalent to: 0.8 l of petrol; 1.3 l of alcohol; 1.4 kg of charcoal; 2.7 kg of firewood; and 1.9 kWh of electricity.

**Table 3.** Biogas generation and energy recovery from UASB sewage treatment plants

| Type of domestic sewage (strength) | Low | Medium | Low |
|---|---|---|---|
| Plant capacity (mld) | 5.00 | 8.00 | 14.00 |
| Biogas yield ($m^3$/kg of COD removed) | 0.15 | 0.15 | 0.15 |
| Biogas generation ($m^3$/day) | 150.00 | 297.00 | 500.00 |
| Total installed load at plant (kWh/day) | 244.00 | 500.00 | 672.00 |
| Generated electricity (at 30% engine efficiency) (kWh/day) | 288.00 | 570.00 | 960.00 |
| Revenue from electricity (Rs in lakhs/annum) | 1.60 | 3.12 | 5.26 |
| Revenue from biogas if used as fuel (Rs in lakhs/annum) | 2.24 | 4.44 | 7.48 |

*Source*. Indo-Dutch Environmental Projects at Kanpur, Chapra, and Mirzapur. IRAMconsult, Inhouse study.

## Technology options for municipal waste water treatment

Under GAP, various technologies for waste water treatment, namely, UASB process, oxidation ponds, activated sludge process, etc. have been tested. A few case-studies of predominant technologies in India have been provided to give a clear picture about their relevance in terms of investments, efficiencies, energy requirements, O & M costs, simplicity, and their sustainability.

Typical characteristics of aerobic and anaerobic processes are highlighted in Table 4.

**TABLE 4.** Typical characteristics of aerobic and anaerobic systems

| Item | Conventional activated sludge | Conventional trickling filter | Oxidation ditch | Facultative aerated lagoon | Waste stabilization ponds | UASB and maturation ponds |
|---|---|---|---|---|---|---|
| Performance | | | | | | |
| • BOD removal (%) | 85–92 | 80–90 | 95–98 | 75–85 | 75–85 | 75–85 |
| • Coliform removal (%) | 60–90 | 60–90 | 60–90 | 60–90 | 60–99.9 | —* |
| • Helminth removal | No | No | No | No | Yes | Yes |
| Land requirement ($m^2$/capita excluding post-treatment) | 0.18–0.25 | 0.20–0 30 | 0.15–0.20 | 0 30–0 40 | 2.02.8 | 0.15–0.20 |
| Energy requirement (kWh/person/year) | 12–15 | 7–11 | 16–19 | 12–15 | Nil | Nil |
| Equipment requirement (excluding equipment screen and grit chamber) | Aerators, recycle pumps, scrapper, thickeners, digesters, dryers, gas equipment | Trickling filter arms, recycle pumps, sludge scrappers, thickeners, digesters, equipment | Aerators, recycle pumps (sludge scrapper for large settlers) | Aerators, only pump | Nil | Nil (gas collection) |
| Level of supervision | Skilled | Skilled | Simpler than activated sludge (except start-ups) | Simple | Simplest | Simpler than activated sludge |

*Insignificant.

*Source.* MNREC. June 1991. *Anaerobic Technology for Domestic Waste Water Treatment.* ISTE Summer School. Allahabad. Motilal Nehru Regional Engineering College.

## Case-studies

### *5 mld UASB treatment plant at Kanpur*

Under the waste water component of the Indo-Dutch project at Kanpur, a 5 mld UASB plant for domestic waste water treatment was constructed for the demonstration of UASB technology under Indian conditions. It was commissioned in April 1989 and the progress and results achieved in the last five years are highlighted below. The schematic flow diagram of the 5 mld UASB treatment plant, shown in Figure 2, highlights clearly the various units of the treatment process.

This plant has been monitored for one year (April 1989 to March 1990) and the following parameters have been analysed: COD, BOD, and TSS treatment efficiencies; biogas yield and biogas quality; sludge loading potential and sludge characteristics, on-site specific sludge methane production, and specific methanogenic activity (SMA). Results achieved are shown in Table 5.

For a biogas yield of 0.10–0.15 $m^3$/kg (COD removed), the quality achieved was as given below.

$CH_4$ estimated—75–80%
$H_2S$—0.5%
$CO_2$—5%
N estimated—14–19%

The overall performance of the UASB reactor was satisfactory with respect to COD, BOD, and TSS removal efficiencies. The sludge age was long enough to guarantee a good process stability and a well-established excess sludge. Based on the sludge stability tests, i.e., the ash contents of the sludge and the absence of malodour, it could be concluded that the excess sludge was sufficiently stabilized. Furthermore, the ability of sludge to settle during the whole investigation period remained satisfactory. The sludge drying characteristics were excellent.

**TABLE 5.** Performance data of the 5 mld UASB treatment plant

| Parameter | Concentration (mg/l) | | Removal efficiency (%) |
|---|---|---|---|
| | Influent | Effluent | |
| COD | 552 | 136 | 75.3 |
| BOD | 222 | 44 | 80.2 |
| TSS | 322 | 68 | 78.9 |

*Source.* Monitoring reports of 5 mld UASB treatment plant at Kanpur.

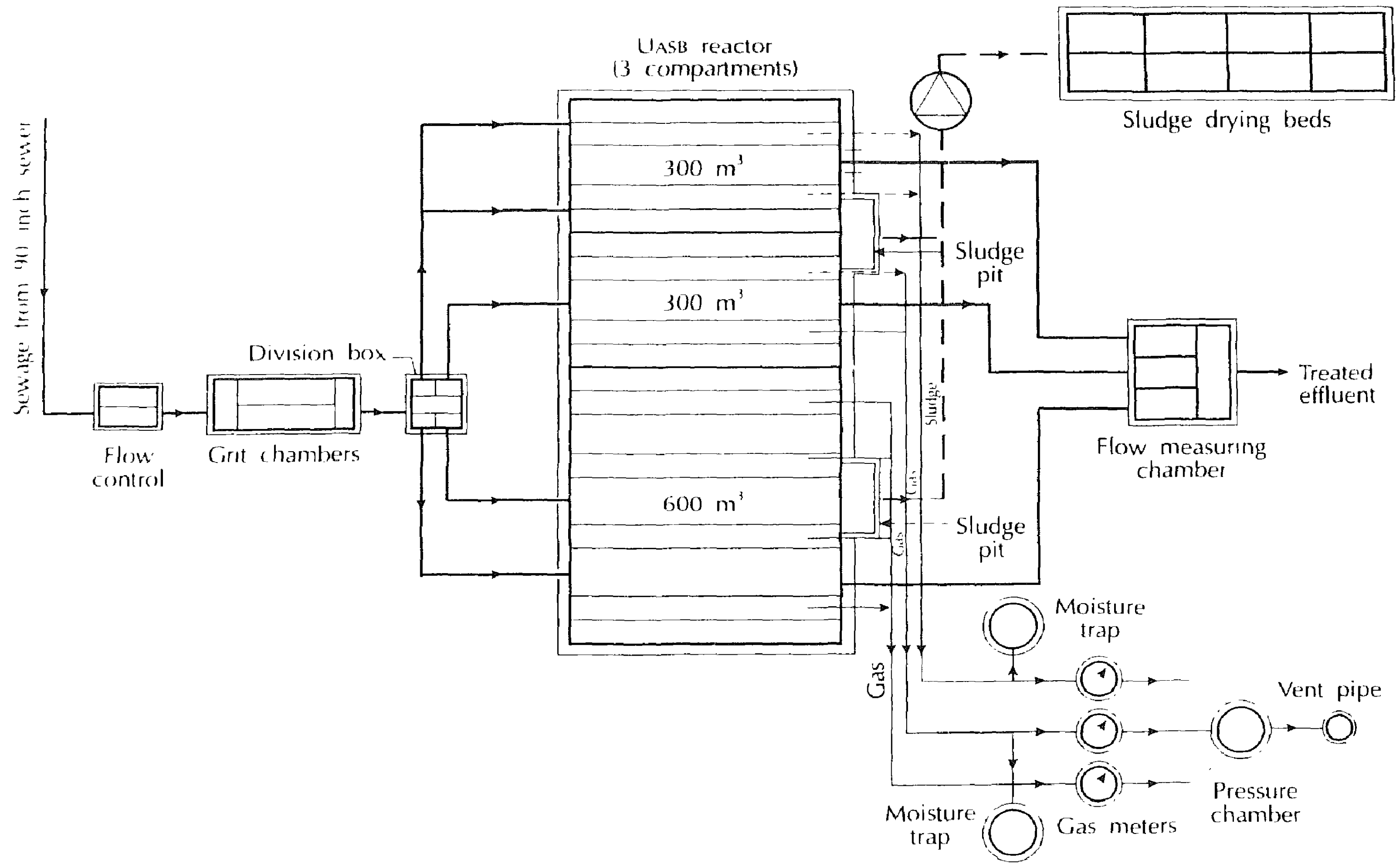

FIGURE 2. 5 mld UASB treatment plant—schematic flow diagram.

The biogas production increased when the sewage temperature went up indicating that there was no change in the sludge quality with respect to methanogenic activity, but merely a temperature effect. The biogas yield achieved was 0.1 $m^3$/kg COD removed. The decrease in biogas production at lower temperature was partly explained by the higher solubility of methane at lower temperatures. However, the main reason for the decrease in biogas production was the temporary lower methanogenic activity of the sludge at lower temperatures.

### *Operation and maintenance costs*

The components contributing to the annual O & M cost of the UASB treatment plant are staff expenses, general maintenance, laboratory expenses, and power consumption. The April 1989–March 1990 O & M cost was Rs 0.625 million. It is also to be noted that in case the capacity of the treatment plant increases, then the O & M cost will remain almost the same with the only exception of power consumption, which increases the cost marginally. Moreover, experience has shown that the actual power consumption is quite low.

### *Energy savings and biogas generation*

The electricity consumption of the UASB waste water treatment plant is considerably lesser when compared to other aerobic treatment plants due to fewer mechanical and electrical components. In the case of 5 mld UASB waste water treatment plant, expenditure on electricity (based on metre readings) is Rs 60 000 per annum. Out of this, 35–40% is incurred on the plant lighting. These figures reveal that the UASB technology has tremendous potential for energy savings.

The quantity of biogas produced at the 5 mld UASB treatment plant is 150 $m^3$/day (based on biogas yield 0.15 $m^3$/kg COD removed). It is estimated that 54 750 $m^3$ of biogas will be generated in one single year. Considering the fact that 1 $m^3$ of biogas can produce electricity equivalent to 1.9 kWh, there is tremendous potential for cleaner technologies like UASB treatment plants.

### *Conclusions*

1. Start-up of the UASB reactor without the use of seeding material is successful and can be achieved in a period of about 10 weeks.
2. Anaerobic treatment of domestic waste water by using the UASB concept is feasible under Indian conditions with satisfactory COD, BOD, and TSS reductions at a hydraulic retention time of six hours. The process stability of the system is good.
3. The compartment provided with baffles showed a better performance with respect to BOD, COD, and TSS removal.

4. A density of one inlet point per 3.7 $m^2$ is sufficient to provide a properly distributed influent.
5. The produced excess sludge has excellent dewatering and drying characteristics and is well stabilized. Within six days, this sludge dries on sludge drying beds and the cakes can be removed manually.
6. During winter, the treatment efficiency and process stability remain good. There occurred a temporary lower biogas production due to a lower sludge methanogenic activity for a period of about three weeks.
7. In order to meet the Indian discharge standards for surface water discharge, post-treatment is required. This post-treatment system is a high rate polishing pond with one day retention time.

*Recommendations*

1. To implement a full-scale UASB plant for treatment of municipal waste water under Indian conditions, the safe operational and design parameters are as follows.

- Sludge loading rate (COD/kg VS/day)—0.3 kg
- Sludge concentration (excluding settler component)—5%
- Aperture velocity—< 5 m/h

2. Attention has to be paid to control the accumulation of floating layers below the gas domes and the gas tightness of the domes.
3. To meet the river water discharge standards, post-treatment is required. The post-treatment system could be a polishing pond with one day retention time.

### *14 mld UASB treatment plant at Mirzapur*

The projected waste water flow to the UASB treatment plant in Mirzapur in the year 2006 is 14 000 $m^3$/day and in 2021 is about 20 000 $m^3$/day. A least-cost analysis indicated that a 14 mld plant be constructed with inbuilt possibilities to expand the capacity in the future by 50%. Laboratory analysis of the waste water in the *nalahs* (sewage canals) of Mirzapur indicates the average composition of the waste water to be: COD = 360 mg/l; BOD = 180 mg/l; TSS = 360 mg/l; and temperature range = 20–31 °C.

The hydraulic design of the plant has been laid out in such a way that no intermediate pumping is required. The main pumping station of the interceptor system, having two pumps + one stand-by pump, each of 660 $m^3$/h capacity, directs the waste water to the inlet chamber, from where it flows under gravity through the reactor and eventually after treatment into a nearby irrigation canal. A bypass arrangement has been made to direct the effluent to the river Ganga during the monsoon period. The UASB reactor consists of two units of 2400 $m^3$ each. The average hydraulic retention time is about eight hours.

The expected quality of the effluent of the UASB plant at Mirzapur is BOD = 50–70 mg/l and TSS = 110–225 mg/l. As the discharge standards in India for irrigation are BOD = 50 mg/l and TSS = 50 mg/l, and for discharge into surface water is BOD = 30 mg/1 and TSS = 50 mg/1, the effluent will receive a post-treatment in a high rate oxidation pond with a retention time of one day. The treated effluent will mostly be used for irrigation purpose nearby.

### *Energy recovery*

The biogas production on the basis of an expected yield of 0.1–0.15 $m^3$/kg COD removed will be about 500 $m^3$ per day with a methane content of 80% (approximately). This gas has the potential to produce 47 kW of electricity. In view of the daily power requirement of the plant (12 kW)—with the minimum and maximum requirements at 3 and 30 kW, respectively—two generator sets of 18 kW with dual-fuel engines have been installed. For the time being, the excess biogas will be flared.

## Financial aspects

The cost comparison between UASB treatment plant and an activated sludge treatment plant (ASTP) is given in Table 6. The cost of the UASB plant with post-treatment is also compared. The costs based on 1991 prices are on actual projects, implemented under GAP at Varanasi and Mirzapur.

It is indicative in Table 6 that capital costs of both the treatment systems vary, the most appreciable difference being in the net annual running costs. It is higher in the case of ASTP (almost eight times that of UASB) and therefore, the gross capital costs per mld of waste water treatment also increase substantially. With the result, the UASB treatment technology becomes cheaper and more cost-effective.

In Table 7, the untreated sewage of the 10 metro cities by the year 2001 has been estimated. The untreated sewage has been estimated at the present level of treatment available. The cost component of waste water treatment, if treated with two different technologies is studied in Table 7.

It can be observed from Table 7 that the costs of waste water treatment by UASB process with post-treatment are about Rs 7720 million less than that of ASTP. The treatment in both cases conform to effluent discharge standards set by the Ministry of Environment and Forests. This proves that the use of the UASB technology is not only cost-effective and technically viable but also provides us with an opportunity to undertake sustainable urban waste water management. The sustainability of the UASB process primarily relates to its comparatively low

**TABLE 6.** Cost comparison between UASB plants and ASTP [costs presented in Rs (millions) per mld]

| Particulars | UASB plants | | |
|---|---|---|---|
| | 14 mld UASB at Mirzapur (with post-treatment) | 14 mld UASB Mirzapur (without post-treatment) | 80 mld ASTP at Varanasi |
| Capital costs (including land, civil works, and E & M installations) | 1.439 | 1.296 | 1.979 |
| Annual operating costs (including energy required, repairs, and staff salaries) | 0.052 | 0.050 | 0.147 |
| Annual cost recovery (electricity from biogas) | 0.037 | 0.037 | 0.028 |
| Net annual running costs | 0.015 | 0.013 | 0.119 |
| Capitalized running costs | 0.127 | 0.113 | 0.962 |
| Gross capital cost | 1.565 | 1.409 | 2.941 |

*Source.* HASKONING, EUROconsult, IRAMconsult, AIC. March 1994. *Integrated Approach and Replicability*. Final report.

**TABLE 7.** Estimated costs of waste water treatment by different systems [all figures are gross capital costs in Rs (million)]

| City | Untreated sewage in 2001 (mld) | UASB with post-treatment | ASTP treatment system |
|---|---|---|---|
| Bombay | 1160 | 1815 | 3410 |
| Calcutta | 1175 | 1839 | 3455 |
| Delhi | 1305 | 2040 | 3840 |
| Madras | 150 | 235 | 440 |
| Bangalore | 125 | 195 | 370 |
| Hyderabad | 650 | 1020 | 1910 |
| Ahmedabad | 145 | 230 | 425 |
| Pune | 200 | 315 | 590 |
| Kanpur | 320 | 500 | 940 |
| Patna | 390 | 610 | 1145 |
| TOTAL | 5620 | 8799 | 16525 |

*Sources* 1/ CPCB. 1989/90. *Status of Water Supply and Waste Water Collection, Treatment and Disposal* (CUPS/30/1989-90). New Delhi: Central Pollution Control Board.
2/ ORG 1989 *Delivery and Financing of Urban Services*. Baroda: Operations Research Group.
3/ Khan A Dinesh K V, Khan K P 1993 Sustainable urban waste water management with special reference to UASB technology. *Technical Workshop on Environmental Management* organized by Center for Environmental Research, Planning and Action, November 1993, New Delhi.

investment and O & M costs, and good options for resource recovery like production of biogas, reuse of treated effluent for irrigation, and use of sludge as manure, which helps in soil enrichment.

## CONCLUSIONS

- Urban waste water management is technically and economically viable if proper selection of technological options is made. Such a choice will enable significant savings in costs and sustainability.
- UASB technology seems to be the best choice for sustainable management and treatment of urban waste water due to its relatively low investment costs and significantly low O & M costs. Also, energy is recovered in the form of biogas. Due to minimal mechanical and electrical components, the process of operation is rather simple.
- It is suggested that the urban environmental infrastructure services will be benefited by adopting the Integrated Approach as highlighted by the Indo-Dutch environmental project at Kanpur and Mirzapur.
- Institutional aspects, which have not been explored in this paper, require adequate attention and thorough overhauling in order to achieve the objective of sustainable municipal waste water management.

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## 11

# The management of infectious wastes

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## INTRODUCTION

Infectious waste is *waste that is capable of producing an infectious disease in man or animal* and is considered as an extreme hazard. It can be the source of diseases like acquired immune deficiency syndrome (AIDS), hepatitis, tuberculosis, and other communicable diseases. It is recommended that each health facility develop a waste management plan.

The major elements of such a plan are discussed in some detail. Treatment using incineration is recommended, as this has the advantage of giving air emissions that can be readily controlled.

An efficient waste management programme—conforming to acceptable safety, health, and environmental standards—is imperative to treat wastes arising from a modern care facility (e.g., hospital and clinic). Four waste streams (listed below) can be identified, each requiring its own management programme.

1. Food and general waste from wards, offices, kitchens, etc.
2. Chemical waste from laboratories, waste drugs, and pharmaceuticals including hazardous materials such as oncology drugs.
3. Radioactive waste such as low level $^{14}C$, $^{127}I$, $^{3}H$ (tritium), and high level $^{57}Co$.
4. Infectious waste.

The last category, infectious waste, will form the major subject of this paper.

## INFECTIOUS WASTE CHARACTERIZATION

### Definition of infectious waste

As indicated above, infectious waste can be defined as waste that is capable of producing an infectious disease in man or animal. Regulatory agencies, hospitals, and research laboratories have differing perspectives and objectives that influence their views. Therefore, there is no universally accepted definition of infectious waste. Moreover, there is inconsistency in the terminology used to define these wastes. For example, the terms infectious, pathological, biomedical, bio-hazardous, toxic, and medically hazardous have all been used to describe infectious waste.

The infectious potential of a waste depends upon (1) the presence of pathogens of sufficient virulence and quantity, (2) the mode of entry, and (3) the resistance of host.

### Categories of infectious waste

1. *Isolation wastes.* Isolation wastes are those generated by hospitalized patients who are isolated to protect others from communicable diseases. At the minimum, wastes from patients with communicable diseases and requiring isolation should be considered infectious waste.
2. *Cultures and stock of infectious agents and associated biologicals.* These are designated as infectious wastes because of the high concentration of pathogenic organisms in these materials. Culture dishes and devices, which are used to transfer, inoculate, and mix cultures, should also be designated as infectious waste.
3. *Human blood and blood products.* These include serum, plasma, and other blood components.
4. *Pathological wastes.* Pathological wastes consist of tissues, organs, body parts, and body fluids, which are removed during surgery and autopsy. All pathological wastes should be considered infectious because of the possibility of unknown infection in patients and corpses.
5. *Contaminated sharps.* Contaminated sharps (e.g., hypodermic needles, syringes, Pasteur pipettes, broken glass, and scalpel blades), which have come into contact with infectious agents during use in patient-care or in medical research or industrial laboratories, present the double hazard of inflicting injury and inducting disease. All sharps used in patient-care should be considered infectious wastes because of the possibility of undiagnosed blood-borne disease (e.g., hepatitis B and AIDS).
6. *Contaminated animal carcasses, body parts, and bedding.* The contaminated carcass parts and bedding of animals that are intentionally exposed to

pathogens during research, production of biologicals, and in the *in vivo* testing of pharmaceuticals should be considered as infectious.

Other materials that may pose a health hazard are contaminated equipment, wastes from surgery and autopsy, miscellaneous laboratory wastes, and dialysis unit wastes.

## INFECTIOUS WASTE MANAGEMENT PLAN

The objectives of an effective infectious waste management programme should be to provide protection to human health and the environment from hazards posed by the waste. It should ensure that infectious waste is handled according to established procedures, i.e., from the time of its generation through its treatment (to render it non-infectious) and to its ultimate disposal. An infectious waste management system should include:

1. designation of infectious waste;
2. handling of infectious waste (segregation, packaging, storage, and transport);
3. treatment techniques;
4. disposal of treated waste;
5. contingency planning; and
6. staff training.

Management options for an individual facility should be selected on the basis of its appropriateness for that particular facility. Factors such as location, size, and budget must be taken into consideration. The selected options should be incorporated into a documented infectious waste management plan. A designated person—*a project champion*—should make sure that the provisions of the management plan are followed.

In an infectious waste management system, there are a number of areas in which alternative operations are available (e.g., treatment techniques for the various waste handling practices). The selection of available options at a facility depends upon a number of factors such as the nature of the infectious waste generated, the availability of equipment for treatment, on- and off-site regulatory constraints, and cost considerations.

### Designation of infectious waste

The major element of an infectious waste management plan is the identification of wastes. As described earlier, six categories of infectious wastes have been identified so far, and other potential wastes should be evaluated on an individual basis by an authorized person.

## Handling of infectious waste

### *Segregation*

Infectious waste should be separated from the general waste in order to be given more attention. Also, segregation of the waste assures that the added costs of special handling will not be applied to non-infectious waste. Infectious waste should be segregated from the general waste stream at the point of generation (i.e., the point at which the material becomes a waste). It is best accomplished by those who generate wastes and, therefore, are best qualified to assess the hazards associated with it. Infectious waste should be discarded directly into containers lined with polyethylene bags so that it can be clearly identified from the general waste stream.

### *Packaging*

Infectious waste should be packaged in order to protect waste handlers and the public from possible injury and disease, which may result from exposure to the waste. Therefore, the integrity of the packaging must be preserved during handling, storage, transportation, and treatment.

The following factors should be considered while selecting appropriate packaging.

- Waste type.
- Handling and transport of the packaged waste (before treatment).
- Treatment technique.
- Special considerations for plastic bags.
- Package identification and labelling.

#### *Waste type*

To provide adequate waste containment, packaging should be appropriate for the type of waste. Waste-tech (Pty) Ltd provides two types of containers.

1. A 142-litre cardboard box, lined with red plastic polyethylene sheet, can be used for all infected materials other than sharps. A maximum weight of 15 kg is recommended. To avoid overloading of the boxes, a smaller container (50-litre capacity) is provided in areas where heavy wastes are generated (e.g., blood banks).
2. Containers of 4, 7.6, and 10-litre capacities for dumping sharps are provided. They are made of high density polyethylene, which is impervious, rigid, and

puncture-resistant and can be incinerated without producing any hazardous gases. The lid is made of polypropylene and contains a slot with a flap. Once the lid is on the container and the flap is tightly closed, access to the contents is possible only forcibly (e.g., by using an implement such as knife or screw driver). The slot also has provision for the removal of various types of needle. The labelling requirements for the containers are discussed below.

### *Handling and transport*

The containers must be sufficiently rigid and leak-proof so that safety is assured during handling and transportation. One of the most important issues is to ensure that the right container is used. The waste must not be compacted in such a way that it could damage the container.

### *Treatment techniques*

Incineration as a treatment technology requires combustible containers, which produce no obnoxious gases and leave only a minimum of residual ash that needs landfilling.

### *Special considerations for bags*

The quality of a plastic bag and its suitability for carrying infectious waste are determined by the raw materials used in its manufacture and the product specifications. Two different criteria—thickness and durability—are often used to judge the suitability of a plastic bag. Therefore, procurement should be based on one or both of these standards. The important consideration is the selection of tear-resistant plastic bags, which maintain their integrity at least until the waste is treated, and thus, prevent dispersal of infectious agents into the environment. One option in areas where tearing does occur is to use double-bagging rather than a single plastic bag. For aesthetic reasons, opaque plastic is preferable as plastic bags contain certain infectious wastes such as pathogens. With opaque plastic, the contents of the bag are not visible. These bags must be contained in rigid cardboard fibre containers.

### *Package identification and labelling*

Packaged infectious waste should be easily identifiable. This may be done by using containers with the distinctive red colour, which indicates bio-hazardous material, while another option is the use of the universal bio-hazardous symbol on all infectious waste packages and containers. Often there may be regulatory requirements such as the use of the word *danger* on all infectious waste packages as in the United Kingdom. Specific transport code [e.g., under the International Maritime Dangerous Goods (IMDG)] is currently being adopted for road transport in many countries.

### *Storage*

Immediate treatment of infectious waste is not always possible or practical. For example, treatment equipment may not be available because of insufficient capacity, malfunction or unavailability of personnel. In such cases, it may be necessary to store the waste. The factors considered while storing infectious wastes are the integrity of packaging, storage temperature, duration of storage, and location and design of the storage area.

### *Transport (on- and off-site)*

Mechanical devices should not be used to transfer or load infectious waste as rupturing of the packaging and dissemination of the waste may result. Trolleys are suitable for moving packaged infectious waste within the facility. These trolleys should be disinfected frequently and should not be used for transporting other materials before decontamination. For off-site transport, the waste should be in closed, insulated, and leak-proof trucks to prevent scattering, spillage, and leakage. The use of appropriate hazard symbols on the trucks should be according to municipal or state regulations.

## Treatment

The purpose of treating infectious waste is to minimize the hazards associated with infectious agents. To be effective, treatment must reduce or eliminate pathogens present in the waste so that it will not pose any hazard to persons who are exposed to it. Since package integrity cannot be ensured during landfilling, shortage of containment may result in disposal of infectious waste into the environment. Therefore, to ensure protection from hazards posed by these wastes, it is usually recommended that all infectious wastes be incinerated at high temperature and the inert ash disposed of in permitted landfill site.

## Disposal of treated wastes

Effectively treated infectious waste is not biologically hazardous and can be mixed with and disposed of as ordinary waste, provided it does not pose other hazards that are subject to state regulations. Incinerator ash can normally be dumped in a sanitary landfill once it has been checked for hazardous substances.

## Contingency planning

The infectious waste management plan should include a contingency plan to tackle emergency situations. It is important that these measures be selected in a

**TABLE 1.** Emergency situations and clean-up procedures

| Situations | Clean-up procedures |
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| Spillage of liquid infectious waste | Protection of personnel, disposal of spill residue |
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timely manner so that they can be implemented quickly, when needed. Table 1 shows a few examples of such situations and actions to be taken against them.

### Staff training

Training of staff is essential and any such programme should include a description of the infectious waste management plan and the assignment of roles and responsibilities for its implementation. Such education is important for all employees, regardless of the employee's role (i.e., supervisor or supervised) or type of work (e.g., technical/scientific or housekeeping/maintenance). Training programmes should be conducted:

- when infectious waste management plans are first developed and instituted;
- when new employees are hired; and
- whenever infectious waste management practices are changed.

This exercise should be an ongoing process so that policies and procedures detailed in the plan can be reinforced from time to time.

## TREATMENT TECHNOLOGIES

The purpose of treating waste is to change its biological character so as to reduce or eliminate its potential for causing disease. The techniques available for the treatment of infectious waste and their advantages and disadvantages are listed in Table 2 (see next page). The most common treatments are incineration and sterilization. Incineration has been discouraged because of the possibility of chlorinated organics, such as dioxins, being discharged from the stack. It must be

*TABLE* 2. *Advantages and disadvantages of infectious waste treatment techniques*

| Technique | Advantages | Disadvantages |
|---|---|---|
| Incineration | Maximum volume and weight reduction; sterile residue; moderate space required; air emissions controlled | Metal, glass, etc. not reduced in volume; complex operation considering environmental factors; requires trained operator; ash disposal may cause a problem |
| Hydropulping | Reduction in volume; provides good disinfection; changes appearance of waste | Adds weight to product; difficult for biomonitoring; chlorine solution discharged to sewer |
| Sterilization | Low cost; low maintenance | Increases waste handling; needs thorough testing programme; no volume reduction; no change in appearnace of the waste |
| Direct irradiation | Positive disinfection; very reliable | Not demonstrated for infectious waste treatment; permitting expensive with special licences; high capital cost; extensive monitoring required; no volume reduction |
| Compaction | Reduces volume; relatively inexpensive | Does not reduce weight; no disinfection; may not render sharps unusable; may cause leakage problems; may cause difficulty with incineration or other treatment |
| Microwaving | Reduces volume of waste; moderate cost | May result in volatile organic carbon emissions; requires strict monitoring programme; biomonitoring difficult |
| Sterilization with compaction | Reduces volume of waste; positive disinfection; low cost; changes appearance of waste | Difficult to biomonitor; no weight reduction |
| Sterilization with grinding | Low cost; good volume reduction; changes appearance of waste; positive disinfection; not difficult to biomonitor | Moderate maintenance required |

remembered that the infectious waste stream is carefully selected and can be controlled. The quantity of chlorinated materials in the waste is normally very small and the use of PVC is actively discouraged in order to minimize the amount of hydrogen chloride and chlorinated organics that can be discharged.

## Incineration

To ensure destruction of all pathogenic organisms, infectious waste must be exposed to high temperature treatment for an adequate period of time. However, specific standards should be established to define minimum operating temperatures. For example, incineration of infectious waste is normally accomplished in dual chamber incinerators, which operate at a minimum temperature of 850 °C in the primary combustion chamber and at 950 °C in the secondary combustion chamber with a minimum gas residence time of two seconds. Irrespective of the operating conditions, they should comply with the emission standards set by the state or local authorities. Typical standards are:

- particulates—180 $mg/m^3$;
- hydrochloric acid—30 $mg/m^3$; and
- oxygen in excess—three per cent.

Destruction removal and efficiency test is recommended to set the operating parameters for the incinerator. This involves the destruction of *typical* waste and an analysis of the stack gases under normal operating conditions. The results should conform to the above parameters. It is recommended that at least one test-run be done in which the emission of volatile organic compounds, particularly chlorinated compounds, is monitored in order to conform with international and national norms. Monitors, which provide continuous information on combustion temperature, waste feed rate, fuel feed rate, and air feed rate are essential for the process.

In addition to operating procedures, design features can also affect the incineration process. For example, mechanical controls can help ensure that infectious waste is exposed to the appropriate combustion temperature. Lock-out devices can be installed to prevent ignition of the primary chamber until the secondary chamber is at operating temperature. Shut-down devices will keep the secondary chamber at operating temperature for a certain period of time after the primary chamber is shut off or until it cools down to a certain temperature.

It should be noted that the greatest influence on the environmental acceptability of an incineration facility is the experience and competence of the operating staff. Auditing of the facilty is essential to ensure the maintenance of the required standards.

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## ACKNOWLEDGEMENTS

This paper is the result of efforts of many of the staff of Waste-tech (Pty) Ltd during the past four to five years. Special thanks to Mrs Jenny Orr, Mr Derek Lubie, and Mr Kevin Bowman for their substantial contribution to the success of the company's Infectious Waste Service. *Infectious Waste Management* by F L Cross, H E Hesketh, and P K Rykowski (published by Technomic Publishing Company, Pennsylvania in 1990), is highly recommended for further information.

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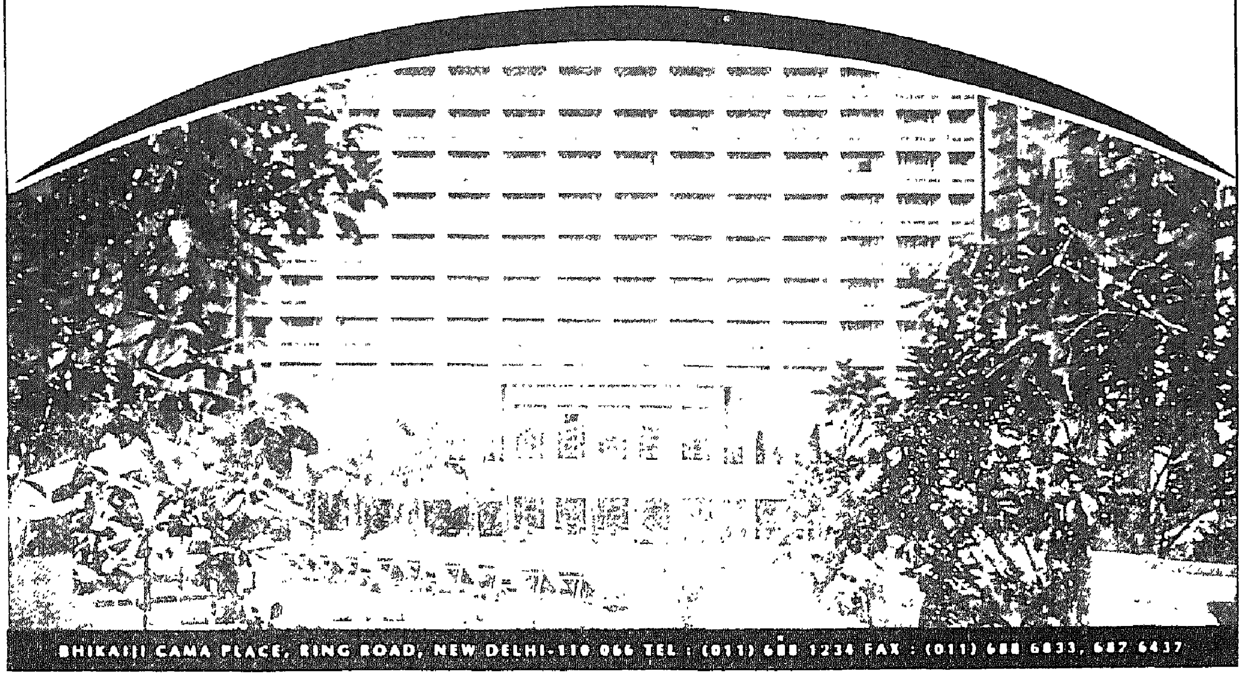

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# 12

# Evaluation of fruit and vegetable processing wastes for bioconversion to methane by anaerobic digestion

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## INTRODUCTION

In recent years our planet has come under severe threat due to environmental pollution caused by rapid industrialization and greater agricultural activities. This problem has attracted the attention of environmentalists, sociologists, scientists, governments, and the public equally all over the world. Treatment of industrial wastes has become an essential part of life in almost all the developed and developing countries. The waste includes solid waste, liquid waste, and effluents from agro and chemical industries. As regards quantity, food processing, agro-industrial, and agricultural residues are by far the largest wastes available, to the tune of 877.2 million tonnes per year, in India (Table 1) [1]. There are over 18 550 food processing industries in India [2]. For processing and utilization, food commodities can be grouped into the following categories: (i) fruits; vegetables; and tubers; (ii) sugar, starch, and confectionery; (iii) grains, legumes, and oilseeds;

**TABLE 1.** Current biomass sources for energy conversion (million tonnes) per year

| Wastes | Sudan | Brazil | India | Sweden | USA |
|---|---|---|---|---|---|
| Sewage | 1.1 | 6.7 | 37.4 | 0.5 | 13.0 |
| Municipal solid waste | 1.9 | 36.0 | 112.9 | 4.4 | 123.0 |
| Manure | 56.7 | 391.9 | 543.8 | 11.0 | 255.0 |
| Agricultural residue | 2.7 | 39.2 | 87.1 | 2.8 | 430.0 |
| Biomass | 144.2 | 372.6 | 96.0 | 10.5 | 320.0 |
| TOTAL | 206.6 | 846.4 | 877.2 | 29.2 | 1141.0 |

*Source.* Vergara W, Pimental D. 1978. *Symposium on Energy from Biomass and Wastes.* 14-18 August 1978 Chicago Institute of Gas Technology

(iv) distilleries, breweries, and winery; (v) plantation products; (vi) meat, poultry, and egg; (vii) fish and marine products; and (viii) milk and dairy products.

In food processing and related industries, the recovery of nutrients and modification of wastes are becoming increasingly important and the combined effect of these steps would make these industries more viable. In view of the strict government regulations, it is obligatory to reduce pollution to the prescribed level. With increasing prices of conventional fuels and also their shortages, the production of energy from organic matter derived from food industry, agro-industrial wastes, agricultural residues, and biomass has become a necessity. Anaerobic digestion has been considered as a simple and economically viable technology for energy production. Along with energy in the form of methane, it also yields spent solids and effluents. Spent solids can be utilized for animal or poultry feed; and effluents, after solid recovery, would be a good feed for aquaculture. Besides, it reduces the level of pollution, and conserves the wastes.

A number of technologies have been developed for the treatment of effluents, and notable among these are anaerobic filter process and upflow anaerobic sludge blanket (UASB) [3, 4]. Both are considered to be economically viable for treating effluents from various processing industries (Table 2). Anaerobic digestion processes, based on UASB modes, are being used for the treatment of industrial waste waters—producing methanol, butylene, glycol, plastic, organic acids, ketones, and acrylates.

Food processing and other solid wastes have not been tried extensively for biogas generation. Lane, in Australia, has attempted to utilize fruit and vegetable processing wastes, especially citrus, at laboratory and bench-scales. It has been reported that a loading rate of four per cent of citrus processing solid wastes could be used for methane generation and a higher level of it would result in a failure of anaerobic digestion [5–7]. The oil present in the citrus peel was found to be inhibitory for the growth of methanogenic microorganisms and methane generation. While carrying out engineering and economic analysis of methane generation from potato, fruit, tomato, and dairy wastes, it was reported that the seasonality of solid wastes was the major hindering factor for the commercialization of the process [8]. Two large-scale plants have been built recently—one using Austrian (BVT-BIMA) liquid manure technology and the other using a Hungarian technology (GATE-DOMSOD) based on a mixed feed containing animal, and fruit and vegetable wastes [9].

**TABLE 2.** Application of fixed bed reactors for the treatment of wastes

| Wastes from various industries | Influent COD (mg/l) | Reactor volume ($m^3$) | Support medium | Hydraulic retention time (HRT) (days) | Loading rate (kg COD/$m^3$/day) | Location/ reference |
|---|---|---|---|---|---|---|
| Starch gluten manufacture | 8800 | 3 × 380 | Graded rock (2.5–7.6 cm) | 0.9 | 03.8 | Spokane, WA |
| Guargum processing | 9100 | 1020 | Pall rings (9 cm) | 1.0 | 16.0 | Vernon, Texas |
| Sugar refinery | 20000 | 2 × 1500 | Graded rock | 0.5–1.5 | — | Northern Italy |
| Vegetable processing | — | 300 | PVC rings | — | — | Piacenza, Italy |
| Sugar beet refinery | 10000 | 2000 | Flocor R | 0.6 | 14.0 | Aulnois, France |
| Winery | — | 5600 | -do- | — | 11.8 | Cognac, France |
| Cane molasses distillery | — | 1700 | -do- | — | 14.1 | La Guadeloupe, West Indies |
| Vegetable canning | 3000 | 430 | -do- | 0.3 | 14.0 | Bierne, France |
| Jam manufacture | 8000 | 430 | -do- | 0.8 | 10.5 | Bretenoux, France |
| Cheese industry | — | 110 | -do- | — | 11.8 | Domency, France |
| Milk processing | — | 4150 | -do- | 0.63 | 10.4 | Ireland |
| Potato processing | 2000–10000 | 1700 | Pall rings | 1.0 | 08.0 | France |
| Starch production | — | 1200 | Pall rings | — | — | France |
| Yeast production | 30000 | 1280 | Polypropylene mini rings | 2.3 | — | Scotland |

*Source.* Iza J, Colleran E, Paris J M, Wu W M. 1991. International Workshop on Anaerobic Treatment Technology for Municipal and Industrial Waste Waters. Summary paper. *Water Science Technology* **24**(8) 1–16

## CFTRI PROGRAMMES ON METHANE GENERATION

Fruit and vegetable processing wastes are a significant source of raw material for the production of biogas by anaerobic digestion. Although correct information about the total availability of these wastes is lacking, about 5.6 million tonnes (a fraction of total production of fruits and vegetables in India) are generated annually (Table 3). Besides these, cabbage, carrot, spinach, greens and beans, and temperate fruits are also processed either by canning or freezing. At the National Dairy Development Board (NDDB) (Fruit and Vegetable Project, Mangolpuri, Delhi), about 30–40 tonnes of greenpea peel emanate daily during processing, for two to three months in a year. It is expected that the processing of greenpeas will increase in future due to the growth of fast foods and increased demand. Disposal of this waste poses serious problems to landfills. If this waste could be used for energy generation from the biogas produced, about 303 100 tonnes equivalent liquified petroleum gas (LPG) can be generated yearly amounting to Rs 5135 billion in terms of industrial gas cylinders. Thus the fruit and vegetable processing wastes represent a significant energy source.

Utilization of these wastes for methane generation by anaerobic digestion is somewhat different from the conventional method of treating sewage or manures or cattle dung. These wastes are rich in cellulose, hemicellulose, lignin and pectin and these are difficult to hydrolyse as compared to partially hydrolysed cattle

**TABLE 3.** Annual production of fruit and vegetable processing wastes in India

| Fruit/ vegetable | Nature of waste | Production ('000 tonnes) | Approximate waste content (%) | Potential quantities of wastes ('000 tonnes) |
|---|---|---|---|---|
| Mango | Peel and stone | 6987.7 | 45 | 3144.4 |
| Banana | Peel | 2378.0 | 35 | 832.3 |
| Citrus | Peel, rag, and seed | 1211.9 | 50 | 606.0 |
| Pineapple | Skin and core | 75.7 | 33 | 24.7 |
| Grapes | Stem, skin, and seed | 20.0 | 20 | — |
| Guavas | Peel and core with seeds | 656.0 | 10 | — |
| Peas | Shell | 107.7 | 40 | 68.3 |
| Tomato | Skin, core, and seeds | 464.5 | 20 | 90.3 |
| Potato | Peel | 2769.0 | 15 | 415.3 |
| Onion | Outer leaves | 1102.0 | — | — |
| Apple | Peels, pomaces, and seeds | 1376.0 | — | 412.0 |
| TOTAL | | 17148.5 | | 5593.3 |

*Source*. Nand K. 1994. Biogas from food wastes. *Indian Food Industry* 13(3): 22.

**TABLE 4.** Proximate composition of food processing wastes (%)

| Constituents | Mango | Tomato | Lemon | Deoiled orange | Orange | Pineapple |
|---|---|---|---|---|---|---|
| Moisture | 73.60 | 70.50 | 11.50 | 12.00 | 11 70 | 06.60 |
| Total solids | 26.40 | 29.50 | 88.50 | 88.00 | 88.30 | 93.40 |
| Volatile solids | 96.50 | 95.73 | 95.80 | 93.60 | 94.20 | 92.20 |
| Ash | 03.50 | 04.30 | 04.20 | 06.40 | 05.80 | 07.80 |
| Total carbon | 39.80 | 54.90 | 42.20 | 43.10 | 42.50 | 38.30 |
| Total nitrogen | 00.56 | 04.20 | 02.46 | 02.22 | 01.09 | 00.85 |
| Ether extract | 08.70 | 21.00 | 07.80 | 00.70 | 04.30 | — |
| Total protein | 03.50 | 23.30 | 15.37 | 13.88 | 06.80 | 05.31 |

*Source.* Nand K. 1994. Biogas from food wastes. *Indian Food Industry* **13**(3): 22.

dung, human excreta, sludge, etc. (Table 4). With this in view, detailed studies have been made on seasonality and total availability of fruit and vegetable processing wastes [10]. Most of these agricultural wastes are processed on a seasonal basis over short periods of time during the year. Hence, collection and storage of these wastes for anaerobic digestion have been a difficult problem. Mango, citrus, pineapple, and tomato are processed in maximum quantity, especially in the southern part of India. Their processing wastes have been selected for detailed studies on methane generation.

Mango peel, rich in carbohydrates, has been found to be deficient in proteins, and therefore, organic and inorganic nitrogen are to be supplemented in order to correct the carbon and nitrogen ratio of 30–20:1. Similarly, citrus contains citrus oil, which inhibits the growth of methanogenic and non-methanogenic microorganisms. Tomato peel and seeds are rich in protein (23.3% DW), whereas lemon (15.65%) and deoiled orange (23.3%) wastes, and orange peel (32.6%) contain very high percentage of pectin on dry weight basis. It appeared from data on the quantity, biodegradability, and chemical characteristics of these selected wastes that they have the potential for biogas generation. A substantial quantity of energy is used annually in the processing industry and the biogas generated from these wastes would partially supplement the energy requirement and thereby reduce the overall expenditure on this head.

## LABORATORY AND BENCH-SCALE STUDIES

As the composition of fruit and vegetable processing wastes differs considerably, operational nutritional parameters were optimized for mango peel, citrus, tomato,

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| Guavas | Peel and core with seeds | 656.0 | 10 | — |
| Peas | Shell | 107.7 | 40 | 68.3 |
| Tomato | Skin, core, and seeds | 464.5 | 20 | 90.3 |
| Potato | Peel | 2769.0 | 15 | 415.3 |
| Onion | Outer leaves | 1102.0 | — | — |
| Apple | Peels, pomaces, and seeds | 1376.0 | — | 412.0 |
| TOTAL | | 17148.5 | | 5593.3 |

*Source.* Nand K. 1994. Biogas from food wastes. *Indian Food Industry* **13**(3): 22.

**TABLE 4.** Proximate composition of food processing wastes (%)

| Constituents | Mango | Tomato | Lemon | Deoiled orange | Orange | Pineapple |
|---|---|---|---|---|---|---|
| Moisture | 73.60 | 70.50 | 11.50 | 12.00 | 11.70 | 06.60 |
| Total solids | 26.40 | 29.50 | 88.50 | 88.00 | 88.30 | 93.40 |
| Volatile solids | 96.50 | 95.73 | 95.80 | 93.60 | 94.20 | 92.20 |
| Ash | 03.50 | 04.30 | 04.20 | 06.40 | 05.80 | 07.80 |
| Total carbon | 39.80 | 54.90 | 42.20 | 43.10 | 42.50 | 38.30 |
| Total nitrogen | 00.56 | 04.20 | 02.46 | 02.22 | 01.09 | 00.85 |
| Ether extract | 08.70 | 21.00 | 07.80 | 00.70 | 04.30 | — |
| Total protein | 03.50 | 23.30 | 15.37 | 13.88 | 06.80 | 05.31 |

*Source.* Nand K. 1994. Biogas from food wastes. *Indian Food Industry* **13**(3): 22.

dung, human excreta, sludge, etc. (Table 4). With this in view, detailed studies have been made on seasonality and total availability of fruit and vegetable processing wastes [10]. Most of these agricultural wastes are processed on a seasonal basis over short periods of time during the year. Hence, collection and storage of these wastes for anaerobic digestion have been a difficult problem. Mango, citrus, pineapple, and tomato are processed in maximum quantity, especially in the southern part of India. Their processing wastes have been selected for detailed studies on methane generation.

Mango peel, rich in carbohydrates, has been found to be deficient in proteins, and therefore, organic and inorganic nitrogen are to be supplemented in order to correct the carbon and nitrogen ratio of 30–20:1. Similarly, citrus contains citrus oil, which inhibits the growth of methanogenic and non-methanogenic microorganisms. Tomato peel and seeds are rich in protein (23.3% DW), whereas lemon (15.65%) and deoiled orange (23.3%) wastes, and orange peel (32.6%) contain very high percentage of pectin on dry weight basis. It appeared from data on the quantity, biodegradability, and chemical characteristics of these selected wastes that they have the potential for biogas generation. A substantial quantity of energy is used annually in the processing industry and the biogas generated from these wastes would partially supplement the energy requirement and thereby reduce the overall expenditure on this head.

## LABORATORY AND BENCH-SCALE STUDIES

As the composition of fruit and vegetable processing wastes differs considerably, operational nutritional parameters were optimized for mango peel, citrus, tomato, and pineapple processing wastes separately in 5 and 10 l bioreactors operated on a semi-continuous mode. The highest yield of gas has been 0.62, 0.37, 0.72, and 0.63 $m^3/kg$ volatile solid (VS) added for tomato, mango, pineapple, and lemon and orange processing wastes, respectively [10]. The carbon:nitrogen:phosphorus (C:N:P) ratio is important for anaerobic digestion and has got profound effect on the specific rate and yield of biogas and methane production from mango peel. Dried mango peel, supplemented with urea for adjusting C:N ratio to 30–20:1, resulted in the stability of digesters and also the higher rate of gas production (Table 5). Agro-industrial and agricultural wastes contain different proportions of nutrients, and the influence of silkworm waste and oilseed cakes such as castor and neem on biogas production from mango peel is shown in Table 6.

Fruit and vegetable processing wastes are seasonal and are available only for a short period (two to three months). During this period, a variety of wastes are

**Table 5.** Different C:N ratio and biogas production from mango peel

| C:N ratio | Biogas yield ($m^3$/kg VS added) | Methane (%) |
|---|---|---|
| 20 | 0.603 | 52 |
| 30 | 0.577 | 49 |
| 40 | 0.483 | 48 |
| Control | 0.174 | 45 |

***Note.*** Nitrogen source—urea; HRT—30 days; loading rate—4% TS.
*Source.* DNES. 1989. *Microbiological Studies on the Conversion of Food Processing and other Related Agro-industrial Wastes for Biogas Production.* (Report No. 5/2/41/85-BE.) New Delhi: Department of Non-conventional Energy Sources, Government of India.

**Table 6.** Effect of addition of nitrogen-rich substrates on biogas production (in a 1:1 proportion from mango peel)

| Feedstock | Biogas yield ($m^3$/kg VS added) | Methane (%) |
|---|---|---|
| Mango peel alone | 0.175 | 45 |
| Mango peel + Silkworm pupae (deoiled) | 0.550 | 60 |
| Mango peel + High ash silkworm waste | 0.515 | 56 |
| Mango peel + Silkworm fibre | 0.384 | 50 |
| Mango peel + Neem cake | 0.338 | 50 |
| Mango peel + Castor cake | 0.496 | 55 |

***Note.*** HRT—30 days; loading rate—4% TS.
*Source.* As in Table 5.

**TABLE 7.** The pattern of feeding of fruit and vegetable processing wastes

| Periods (25 days each) | Feedstock (wastes) used for five days each in succession |
|---|---|
| 1 | Tomato, banana, jackfruit, orange peel with oil, pineapple |
| 2 | Tomato, jackfruit, mango, pineapple, deoiled orange |
| 3 | Pineapple, mango, jackfruit, pineapple, tomato |
| 4 | Banana, deoiled orange, jackfruit, pineapple, mango |
| 5 | Tomato, orange peel with oil, jackfruit, banana |

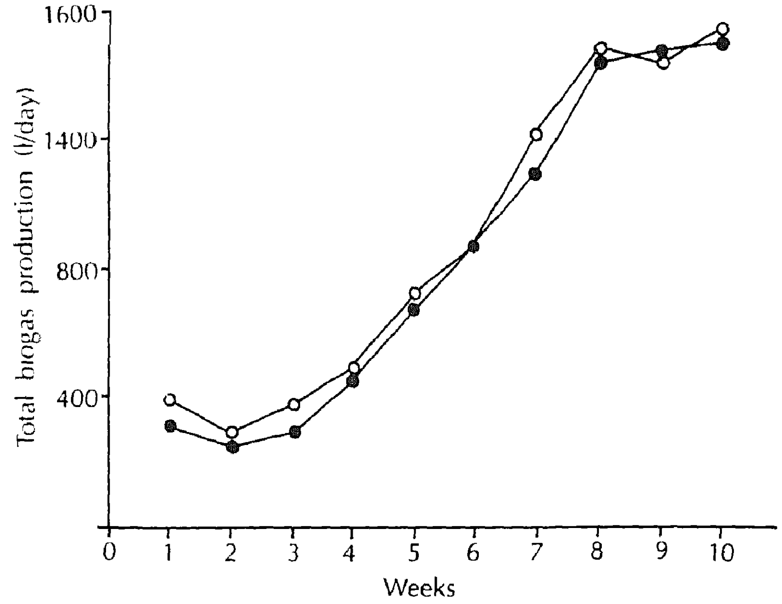
*Source.* Viswanath P, Sumithradevi S, Nand K. 1992. Anaerobic digestion of fruit and vegetable wastes for biogas production. *Bioresource Technology* **40**: 43.

generated in the processing industry. It is, therefore, necessary to operate the digester with the wastes available during the season. Viswanath *et al.* studied the effect of feeding different fruit and vegetable wastes (mango, pineapple, tomato, jackfruit, and banana) in a 60 l biogas digester [11]. With minor manipulations in the nutritional and operational parameters, it was possible to run digesters for a longer time without any noticeable changes in the rate and yield of biogas and methane (Table 7). Stabilization of digesters is needed for operating the system for more than five to six years [12]. In the case of some operational problems, recleaning and recharging with the fresh starter culture will be necessary. Start-up techniques are widely practised for conventional, non-conventional, and advanced reactors [13]. Studies on this have been made using fruit and vegetable processing wastes. A good stabilization of digesters has been achieved by the step-wise addition of feedstock over 10–12 weeks of anaerobic digestion with tomato processing wastes [14] and lemon, lime, orange, and pineapple processing wastes in 1.5 $m^3$ Khadi Village and Industries Commission (KVIC) digesters (Figure 1; see next page).

Scaling-up trials using mango peel, citrus, and tomato processing wastes in 1.5 $m^3$ KVIC digesters have been conducted. An average yield of 1.0–1.2 $m^3$ per day has been achieved with a methane content of 55% at 8–10% of loading rate and HRT of 25 days. The yield and rate of biogas have been affected by the change in temperature, the highest being in April and May and the lowest during the winter season [10].

## Pilot and full-scale anaerobic digestion

Solid wastes of food processing industries at pilot or full-scale methane generation have not been extensively studied except for a few reports [15–19]. Constant *et al.* have reported that potato peelings in potato chips factory in Finland are



*Note.* •—Digester A; o—Digester B. Pattern of feeding: 0-2 weeks—cowdung (CD) (100%); 2-4 weeks—CD:Mango processing waste (MPW) (75:25); 4-6 weeks—CD:MPW (50:50); 6-8 weeks—CD:MPW (25:75); 8-10 weeks—MPW (100%).

**FIGURE 1.** Start-up studies on anaerobic digestion of fruit and vegetable processing wastes (1.5 $m^3$ digesters—Sangli).

utilized for biogas generation in 106 $m^3$ plug-flow digesters and the gas produced is directly used in a boiler as a substitute for energy [20]. Based on the results in 60 l and 1.5 $m^3$ KVIC digesters with mango peel, orange, tomato, lemon, and pineapple processing wastes, biogas generation from mango peel (dried) in 25 $m^3$ KVIC digesters was attempted in order to get reproducible results and also to confirm the technical feasibility of the process for successful commercial operations [10, 14, 21–24]. It was possible to successfully scale up the process with mango peel (dried) obtaining as high as 0.6 $m^3$/kg VS added biogas with 52% methane at 8–10% loading rate and 25-day HRT (Tables 8a & b) [25]. Mahadevaswamy and Venkataraman have reported a yield of 0.21 $m^3$ biogas/kg TS added from mango peel. They also found that the effluent could be a good feed for carp Rohu (*Labeo rahita*), and common carp (*Cyprinus carpio*) yielded 8.35 kg of fish from 34 kg of mango peel effluent after anaerobic digestion [26].

## Effect of additives and stimulants

A number of additives and stimulants have been tried to improve the biological productivity of methane generation from mango, citrus, pineapple, and tomato

**Table 8a.** Scale-up studies in 25 $m^3$ KVIC digesters: influence of loading rate on biogas and methane yield

| Loading rate (%) | Biogas yield ($m^3$/kg VS added) | Methane (%) |
|---|---|---|
| 4 | 0.42 | 46 |
| 6 | 0.50 | 49 |
| 8 | 0.60 | 52 |
| 10 | 0.62 | 52 |
| 12 | 0.25 | 40 |

*Source.* MNES. 1993. *Pilot-scale Studies on Methane Generation from Fruit and Vegetable Processing Wastes.* (Report No. 5/2/29/88-BE.) New Delhi: Ministry of Non-conventional Energy Sources, Government of India.

**Table 8b.** Scale-up studies in 25 $m^3$ KVIC digesters: effect of different HRT on biogas and methane generation

| HRT (days) | Biogas yield ($m^3$/kg VS added) | Methane (%) |
|---|---|---|
| 20 | 0.35 | 45 |
| 25 | 0.60 | 52 |
| 30 | 0.55 | 50 |

*Note.* Substrate—mango peel, loading rate—8%.
*Source.* As in Table 8a

processing wastes (Figure 2; see next page). Supplementing the feed (mango peel) with urea, castor-oil seed cake, rice-bran, and rice-bran oil has also been studied and the highest yield of biogas recorded was with the last mentioned. The influence of trace elements ($Co^{2+}$, $Ni^{2+}$, and $Fe^{3+}$) has been studied with mango peel; although supplementation of trace elements did not increase biogas production it certainly increased the methane content up to 60% [27]. Sugarcane filter mud (SFM), a waste product of sugar processing industry, was employed as a stimulant since it is a good source of n-triacontanol—a plant growth regulator—for biogas generation from mango peel in the ratio of 1:20. It increased biogas and methane yield substantially from 50 to 60% [28].

Surfactants and related compounds are known to agglomerate microbial cells. Therefore, the effect of varying concentrations of the extract of nirmaliseeds, hybrid beans, blackgram, and guargum seeds on biogas production from mango peel was investigated and their addition at the rate of 2–4% enhanced the gas production significantly. Lower concentrations of guargum have also been tried to study its influence on the rate and yield of methane [29]. The influence of

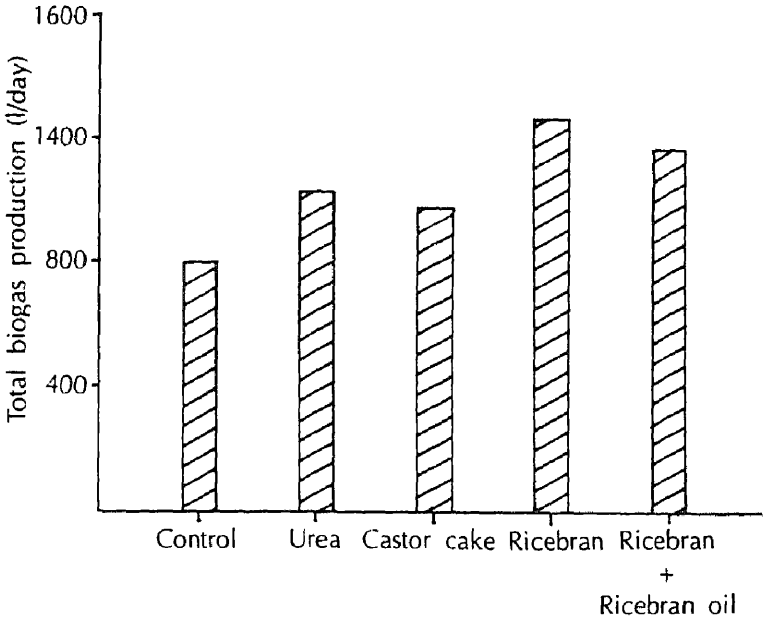


**FIGURE 2.** Effect of additives on biogas production from food and vegetable processing wastes (1.5 $m^3$ KVIC digesters—Sangli).

n-triacontanol was studied on biogas from mango peel which exhibited a considerable effect on the rate and yield of biogas.

## ENSILAGING OF FRUIT AND VEGETABLE PROCESSING WASTES

Fruit and vegetable processing wastes are available only for two to three months during the season and therefore, their utilization and disposal have become a serious problem. Drying of these wastes and preprocessing before anaerobic digestion add enormously to the cost of methane, a terminal product of the process. Ensilaging, which is used for the storage of forage crops and other agricultural commodities, has been employed for mango peel, citrus, and pineapple processing wastes. Laboratory studies made on the ensilage of mango peel proved that it helped storage for a longer period and in the hydrolysis of polymeric constituents, such as cellulose, hemicellulose, and pectin. The biogas yield was as high as 0.68 $m^3$/kg VS added with a methane content of 52% [30]. Preliminary studies, using fixed bed reactors for biogas generation from ensiled mango peel, have been carried out with PVC plugs, iron ore, and clay minerals as support materials. The maximum biogas yield was 0.71 $m^3/kg$ VS added with 61% methane at four per cent loading rate and HRT of 20 days. Ensilaging of orange peel, greenpea peel, and pineapple processing wastes is being attempted to develop an economically viable process for the storage.

## Microbiological pretreatment of feedstocks

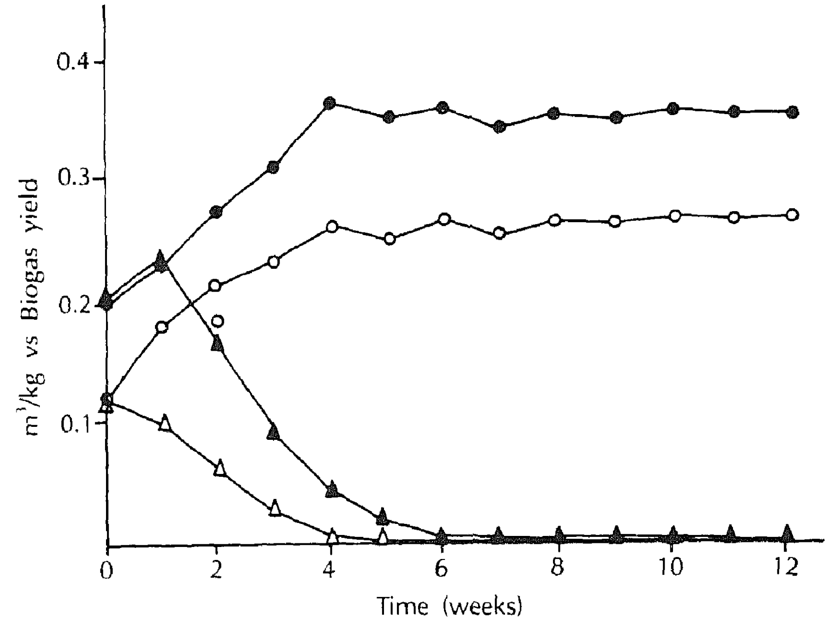
Agro-industrial and fruit and vegetable processing wastes are recalcitrant to biodegradation due to the presence of complex-natured polymeric constituents such as lignocellulosics. These polymeric constituents increase HRT thereby affecting the overall productivity of the anaerobic digestion process. If feedstocks are pretreated, a better utilization of substrate is expected with enhanced methane production and increased rate and extent of hydrolysis of biopolymeric constituents.

An improved rate and yield of biogas and methane was achieved when mango peel was microbiologically pretreated [31]. Pretreatment of orange processing wastes was attempted by selected strains of *Sporotrichum, Aspergillus, Pencillium,* and *Fusarium* sp. separately and their mixed consortium (Table 9). The result was stability in 1.5 $m^3$ digesters yielding 0.5–0.6 $m^3/kg$ VS added with 55% methane at a loading rate of eight per cent at 25-day HRT (Figure 3; see next page).

**Table 9.** Proximate composition of pretreated orange processing waste (%)

| Characteristics | Control | Pretreated orange |
|---|---|---|
| Total solids | 89.30 | 35.00 |
| Moisture | 10.70 | 65.00 |
| Volatile solids | 96.04 | 89.39 |
| Ash | 03.96 | 10.61 |
| *On dry weight basis* | | |
| Cellulose | 10.20 | 07.25 |
| Hemicellulose | 09.15 | 07.09 |
| Pectin | 11.43 | 08.80 |
| Fat | 15.49 | 13.44 |
| Protein | 09.18 | 12.45 |
| Lignin | 10.80 | 10.00 |
| Reducing sugar | 16.20 | 05.60 |
| Non-reducing sugar | 13.00 | 27.20 |

*Source.* Madhukara K, Nand K, Raju N R, Srilatha H R. 1993. Ensilage of mangopeel for methane generation *Process Biochemistry* **28**: 119.



*Note.* Control: ▲—Biogas; △—Methane; Treated: O—Biogas; ●—Methane.
**FIGURE 3.** Effect of microbiological pretreatment of mango peel for biogas production.

## REDUCTION OF BOD AND COD

According to central and state pollution control boards in India, the BOD and COD levels of digested slurry cannot be reduced by anaerobic digestion. It was attempted by recycling the effluent of digesters for preparing the feed every day. Experiments were conducted in 6.5 l and 1.5 m$^3$ digesters using mango peel and orange peel as feedstocks. (The feed was prepared using water and effluent in the ratio 1:1.) The digesters were operated for nine months without any adverse effect on the biogas production. It was found that the BOD of the effluent was reduced to 50% (Table 10). Attempts were also made to recycle the effluent completely for feed preparation to avoid entirely the disposal of effluent to the sewage system. When the effluent was passed through a filter developed in the laboratory, the BOD level was reduced from 5000 to 400 mg/l.

## PROCESS ECONOMICS

The future of anaerobic digestion of fruit and vegetable processing wastes depends on the cost-competitiveness of the biogas produced and also the economic

**TABLE 10.** Recycling of digester effluent

| Time (weeks) | Biogas yield ($m^3$/kg VS added) | | |
|---|---|---|---|
| | Control | 50% recycling | 100% |
| 1 | 0.14 | 0.21 | 0.24 |
| 2 | 0.16 | 0.22 | 0.26 |
| 3 | 0.18<br>(45%) | 0.25<br>(48%) | 0.28<br>(50%) |
| 4 | 0.22 | 0.29 | 0.31 |
| 5 | 0.27<br>(45%) | 0.31<br>(51%) | 0.47<br>(53%) |
| 6 | 0.32 | 0.38 | 0.50 |

***Note.*** Loading rates—8%; feed—MPW; HRT—25 days; working volume of digester—4 l. Figures in parentheses indicate methane content of biogas.

*Source.* MNES. 1994. *Operation and Process Control for Biogas Production* (Report No. 5/2/20/91-BE.) New Delhi: Ministry of Non-conventional Energy Sources, Government of India.

viability of the process. A comparative assessment of biogas production from mango peel at domestic, community, and industrial level is shown in Table 11 (see next page). By making a meagre investment of Rs 8000, if subsidy is provided by the Government of India, a good benefit could be derived and the capital investment could be recovered within a period of 1.5 years. In the case of community biogas plants using two 25 $m^3$ KVIC digesters, the cost of production is marginally higher and the payback period extends to 2.8 years. For the industrial operation of 100 $m^3$ plant, more R & D work is required on the mechanization of different stages of the process.

## CONCLUSION

Disposal of fruit and vegetable processing wastes has been creating a serious problem to public, industry, health, and municipal corporation authorities due to their putrescible nature. The integrated approach, as discussed in this chapter, has three distinct advantages.

1. The methane produced by anaerobic digestion of these wastes is a good substitute of energy.
2. The digested slurry can be utilized as fish or animal feed supplement.

**TABLE 11.** Techno-economics of biogas production from fruit and vegetable processing wastes

| Parameters | Type of biogas plants | | |
|---|---|---|---|
| | Domestic ($4\ m^3$) | Community ($25\ m^3$; 2 nos) | Industrial ($100\ m^3$) |
| Capital cost (Rs) | | | |
| • Biogas digester | 12000 | 225000 | 310000 |
| Less subsidy (50%) | 6000 | 112500 | 155000 |
| Net cost | 6000 | 112500 | 155000 |
| • Pits ($8\ m^3$) (earthen pit with PVC lining) | 2000 | 60000 | 80000 |
| | | | 125000 (mechanical operations including electricity) |
| Net cost | 8000 | 172500 | 360000 |
| • Operational cost | 1000 | 30000 | 60000 |
| Recovery of biogas (per annum) | | | |
| • $m^3$ | 1460 | 36500 | 65700 |
| • Rs | (2120) | (54150) | (95400) |
| • Equivalent fuel value (Rs) | | | |
| LPG | 4620 | 115240 | 471217 |
| Electricity | 2920 | 73000 | 136984 (furnace oil) |
| Kerosene | 2715 | 67890 | — |
| Firewood | 5067 | 126655 | — |
| Sludge solid recovery after anaerobic digestion (Rs) | 3000 | 60000 | 120000 |
| Payback period (years) | 1.5 | 2.8 | 2.6 |

*Source.* MNES. 1994. *Operation and Process Control for Biogas Production.* (Report No. 5/2/20/91-BE.) New Delhi: Ministry of Non-conventional Energy Sources, Government of India.

3. The effluent after solid separation may be used as manure or nutrient for aquaculture. This approach is economical compared to other anaerobic digestion processes. The energy availability potential from fruit and vegetable processing wastes is substantial. Rural areas, especially the weaker section of people, will benefit more by this approach and their dependence on other fuels such as cattle dung could be completely avoided.

The economic analysis using 25 $m^3$ KVIC digesters operated with mango peel, citrus, and pineapple processing wastes reveals conclusively that the methane produced can compete with the energy prices of LPG and other sources of energy. This technology is simple, economical, and cost-effective and is available for commercial exploitation.

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### 13

# Power generation based on distillery spentwash

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## INTRODUCTION

Industrial growth in this country has been phenomenal in recent years, thanks to the significant contribution made by organic chemical industries. Many agro-based industries, such as distilleries, paper and pulp, and rayon grade pulp, discharge highly concentrated organic effluents, which exert considerable stress on aquatic environment. These industries, therefore, must search for an appropriate technology to treat the effluents in order to protect the environment.

Conventional treatment of such effluents is highly revenue-intensive with no payback. Besides, it requires a large space. With the advent of high-rate anaerobic processes, it has become possible to treat these effluents at lower revenue costs and to substantially reduce the organic load on subsequent aerobic treatment. In the process, biogas, a clean fuel, is generated making the payback very attractive. Considering the need for the treatment of effluents, *Western Paques India Ltd* have acquired high-rate anaerobic technology patented as *Biopaq*. The various high-rate anaerobic reactor systems available in India can be classified based on their designs as: (1) completely stirred reactors; (2) fixed film reactor; (3) fluidized bed reactors; (4) bulk volume reactors; and (5) upflow anaerobic sludge blanket (UASB) reactors. Of these designs, UASB reactors are the most popular worldwide.

The *Biopaq* system has been supplied on a turnkey basis to various organic chemical industries, ranging from distilleries to petrochemicals. All these plants are working satisfactorily and the biogas produced is being used to supplement the existing fuels, thus achieving substantial savings in fuel bills.

It was felt that biogas can be more effectively utilized to generate electricity. For the purpose of establishing this alternative source, numerous trials have been conducted at the Western Paques Technology Centre. It has been found that it can be effectively and economically used to generate electric power by using gas/dual fuel engines. In this paper, various options for utilizing this non-conventional energy source are discussed. The major options are: (1) as boiler fuel to replace conventional fuels; and (2) for electric power generation through the use of gas/dual fuel engines. A typical case-study based on effluent from molasses-based distillery has been presented.

## THE *BIOPAQ* TECHNOLOGY

The heart of the *Biopaq* system is the anaerobic reactor based on the UASB process (*Biopaq* UASB). A schematic diagram of the system is shown in Figure 1. It consists of a corrosion-resistant reactor with a unique three-phase settler to separate the sludge, biogas, and the effluent. This settler is located at the top of the reactor and is designed for specific chemical oxygen demand (COD) reactor loadings and hydraulic throughput. A flow distribution network is located at the base of the reactor. This network is designed in such a way that the flow is distributed evenly throughout the bottom of the reactor. This eliminates short-circuiting and promotes proper settling of the sludge. This is a critical factor in reactor operation. The network also facilitates easy cleaning, thereby eliminating potential plugging problems.

New bacterial cells formed in the reactor aggregate into tiny granules with extremely good settling characteristics. The biogas produced by the bacteria is in

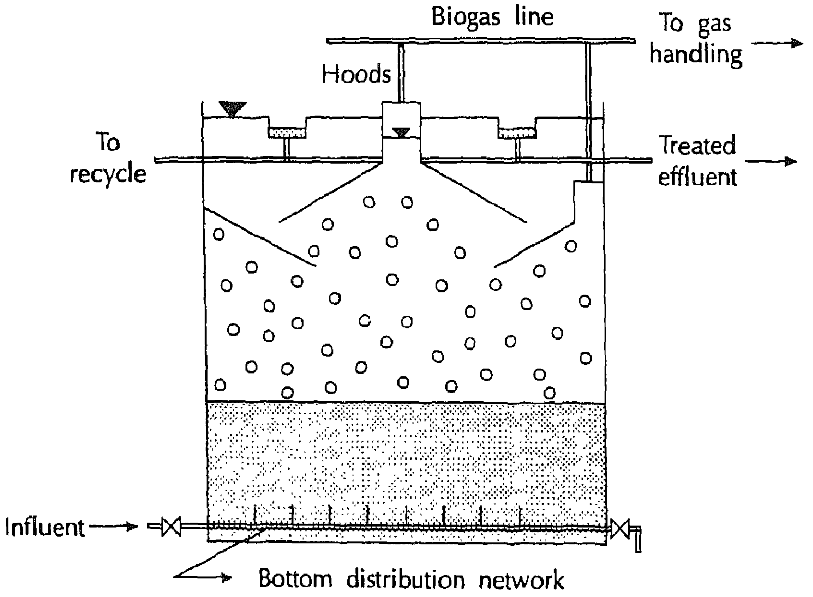

**FIGURE 1.** Schematic diagram of the *Biopaq* system.

the form of small bubbles, thus providing a natural mixing action. When it reaches the top of the reactor, it is removed by gas collectors. A gas-free zone above the collector makes the settling of the finally dispersed solid possible at the bottom of the reactor. Other specific features include:

- high treatment efficiency;
- ability to withstand organic shock-loading;
- directly combustible gas;
- low space requirement;
- low sludge production;
- ability to withstand hydraulic shock-loading;
- low operating and maintenance cost; and
- storage of sludge for longer duration (bacteria stay dormant).

The increased interest shown by industries in anaerobic waste water treatment systems, particularly the *Biopaq* UASB reactor, is due to the advantages (listed below) of this type of installation over other systems.

1. *High loading rates and high treatment efficiencies.* The ability to operate at high organic and hydraulic loads with high removal efficiency allows construction of smaller reactors. This, in turn, leads to reduced capital and operating costs.
2. *Low energy requirements.* Recirculation ratios are dependent on waste type but generally are in the 1:1–1:5 range.
3. *High gas production.* Biogas production can be as high as 0.5–0.55 $m^3$/kg COD reduced.
4. *Quick start-up.* The sludge for the reactor can be transferred from other operating reactors and is highly active. This permits start-up to load fully in approximately two to three months. Most other anaerobic systems take four to six months for start-up.
5. *Sludge recovery.* The sludge is highly concentrated and can be easily dewatered.
6. *Dilution effect.* The system is designed on the basis of organic load and is independent of hydraulic throughput. Except for low waste water concentrations, increased hydraulic flow, due to dilution of water, does not affect the reactor costs and sizing.
7. *Temperature.* The *Biopaq* process has been proven at full scale in the temperature range of 15–40 °C. This means that temperature constraints are minimized in system operation.
8. *Additional features.* Internal gas/liquid/solids separator, constructed of specially treated steel, permits increased sludge retention capacity and efficiency when compared to other anaerobic systems. The choice of the right material eliminates corrosion concerns.

9. *Insensitivity to peakloads.* Special construction of the influent distribution system guarantees good waste water/sludge contact and prevents short-circuiting, plugging, dead zone formation, and eliminates corrosion.

## Pre-acidification/buffer tank

In most applications, a pre-acidification/buffer tank is located upstream from the *Biopaq* reactor. This tank is required to buffer: (i) peak hydraulic loads; (ii) peak organic loads; (iii) extremes in temperature fluctuations; and (iv) to acidify the waste water when required. It can also accept reactor effluent for buffering purposes and chemical nutrients to facilitate pre-acidification when required.

## Sludge disposal

The excess sludge produced in the reactor is very low. It can be easily removed from the reactor applying hydrostatic pressure directly into the tank, and can be applied on land as it has very good manurial value.

## Biogas handling

Biogas is discharged from the top of the reactor and is collected in a common header for discharge to the storage system. Performance of the reactor under different conditions is given in Table 1.

TABLE 1. Performance results

| Condition | Result obtained |
|---|---|
| BOD* reduction | 90–92% |
| COD reduction | 65–75% |
| Temperature of reactor | Mesophilic condition |
| Biogas production | 0.5–0.55 $m^3$/kg COD reduction |
| Methane content | 60–70% |
| Sludge generation | 0.03–0.07 kg/kg COD reduction |

*Biological oxygen demand.

## CASE-STUDY

Based on *Biopaq* technology, several plants have been supplied with equipment for treatment of distillery spentwash. These plants are working satisfactorily and

TABLE 2. Successful case-studies

| Parameter | Haryana Distilleries, Yamunanagar | Sanjivani SSK, Kopargaon |
|---|---|---|
| Spentwash flow | 375 $m^3$/d | 700 $m^3$/d |
| COD | 100000 mg/l | 90000-100000 mg/l |
| BOD | 50000 mg/l | 45000 mg/l |
| COD removal efficiency | 65-70% | 65-70% |
| BOD removal efficiency | 90-92% | 90-92% |
| Gas production | 13100 $m^3$/d | 24000 $m^3$/d |
| Equivalent coal | 17.3 tonnes/day | 31.8 tonnes/day |
| Savings net in operating cost | Rs 8100000/annum | Rs 14700000/annum |
| Payback (in years) | 2.9 | 2.8 |

are giving the desired performance. For the purpose of case-studies, the data of two plants—Haryana Distilleries Limited, Yamunanagar and Sanjivani SSK, Kopargaon (Maharashtra)—have been considered and tabulated (Table 2). From the examples cited, it is quite evident that the effluent treatment can generate profits and the payback for effluent treatment plants can be realized well within three years.

## NEW DEVELOPMENT

Large quantities of biogas have been generated with the help of *Biopaq* systems. Therefore, a suitable scheme has to be developed to utilize biogas for generating electricity. For this purpose, extensive trials have been conducted on gas engines and dual fuel engines to establish various designs and operating parameters. Studies have been carried out to discover the possibility of generating electric power through dual fuel engines using biogas and diesel economically. The findings of a typical 45 000 l distillery are given in Table 3 (see page 251).

A worldwide survey has been carried out to obtain the best possible mode and efficiency on dual fuel engines for designing an optimum system under Indian conditions. A power generation scheme has also been developed for carrying out cost-benefit analysis.

### Power generation scheme

A typical flow sheet, showing the effluent being taken to the buffer tank, is shown in Figure 2 (see next page). The pH, temperature, and COD concentrations

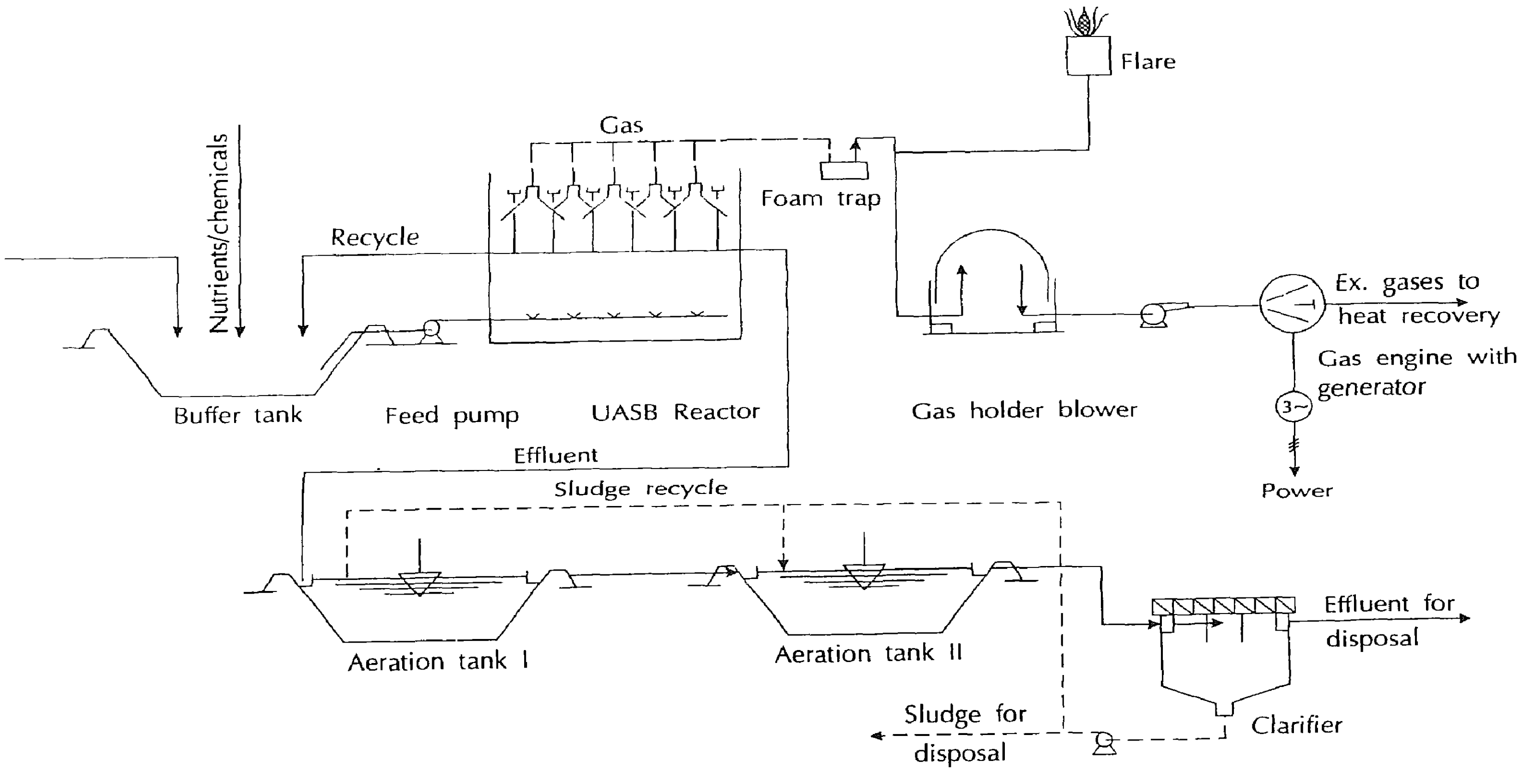

**FIGURE 2.** Effluent being taken to the buffer tank—a typical flow sheet.

**TABLE 3.** Equivalent fuel replacement/power generation with biogas

| Parameter | 45000 l/day distillery |
|---|---|
| Cod reduction | 45500 kg/day |
| Gas generation | 22750 $m^3$/day |
| Heat value of gas | 120.58 $10^6$ kcal/day |
| Equivalent fuel | |
| • Coal | 30.1 tonnes/day |
| • Oil | 11.8 tonnes/day |
| Power generation | 2300 |
| Steam generation waste heat | 1.4 tonnes/h |
| High speed diesel consumption as pilot fuel | 41 l/h |

are adjusted before feeding to the reactor and the required doses of nutrients are added to the buffer tank.

The effluent then enters the *Biopaq* reactor. The bacteria convert organic matter in the effluent to biogas. The biogas generated in the system is stored in a gas holder, which acts as a storage between generation and consumption.

The biogas generated, having a methane content of about 65% and calorific value of about 5300 kcal/$m^3$, will be used as fuel in gas/dual fuel engines. High speed diesel (HSD) is used as a pilot fuel for ignition in the case of dual fuel engines. The engines are coupled with an A.C. generator through suitable coupling. The generated power at 415 V or 11 kV will be supplied to the adjacent industry for captive consumption and the excess power will be supplied to the state grid at stepped-up voltage. The gensets can run in synchronization with the state grid.

A heat recovery system is installed to recover heat in the engine exhaust gases before letting them out to the atmosphere. Recovered heat will be in the form of steam or hot water, which can be used in the process.

## CONCLUSION

It has been established that it is possible to treat effluents of high organic contents by high-rate anaerobic digestion, and the biogas produced can be effectively utilized as a non-conventional energy source with quick payback. The economics of using biogas as fuel for power generation is very attractive, and various financial packages have been developed to fulfil customer needs.

# 14

# Waste management options and technologies for the treatment and disposal of hazardous waste

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## INTRODUCTION

The most important approach for the management of wastes is that of Integrated Waste Management (IWM). It recognizes that it is better to reduce the generation of waste than to incur the costs and risks of managing it. A waste minimization approach is outlined, in order to save costs and greatly minimize environmental liability. In this paper, the waste management options for hazardous waste and the technologies related to it are described. Technologies for the treatment and disposal of infectious waste are also considered.

## WASTE MANAGEMENT OPTIONS

One of the essential components of any successful waste management programme to control hazardous waste is the IWM approach. Thus, in order of preference, any such project should have the following options.

- waste avoidance—waste reduction at source;
- waste recycling, recovery, or utilization;
- waste treatment; and
- waste disposal.

The first two options, and to a limited extent, waste treatment also, comprise the techniques that are commonly termed Waste Minimization.

## Waste minimization

In its broadest sense, waste minimization is any action taken to reduce the volume and toxicity of waste. It includes waste avoidance, waste recycling, recovery and utilization, and certain forms of waste treatment. Technologies such as incineration, chemical detoxification, and biological treatment of waste can lead to a major decrease in the toxicity and volume and thus a minimization of the pollution potential of waste when disposed of, e.g., by landfilling. In this section, however, waste reduction at source and recycling have been emphasized.

Appropriate definitions given by the United States Environmental Protection Agency (US EPA) are given below.

- *Waste minimization.* This includes any source reduction or recycling activity undertaken by the generator that results in either (i) the reduction in the total volume or quantity of hazardous waste, or (ii) the reduction of toxicity of the hazardous waste, or both, so long as such reduction is consistent with the goal of minimizing present and future threats to human health and the environment.
- *Reduction at source.* Any activity that reduces or eliminates the generation of hazardous waste at source, usually within a process.
- *Recycling.* A material is *recycled* if it is used, reused, or reclaimed. A material is *used or reused* if it is either (i) employed as an ingredient (including its use as an intermediate) to make a product [however, a material will not satisfy this condition if distinct components of the material are recovered as separate end products (for example, when metals are recovered from metal containing secondary materials)] or (ii) employed in a particular function as an effective substitute for a commercial product. A material is reclaimed if it is processed to recover a useful product or if it is regenerated. Examples include the recovery of lead values from spent batteries and the regeneration of spent solvents. A diagrammatic representation of waste minimization techniques is shown in Figure 1.

A thorough waste minimization audit should be carried out from which the waste generator can derive considerable benefits such as:

- saving money by reducing waste treatment and disposal costs, raw material purchases, and other operation costs;
- meeting any national waste minimization goals;
- reducing potential environmental liabilities;
- protecting public and workers' health and safety; and
- protecting the environment.

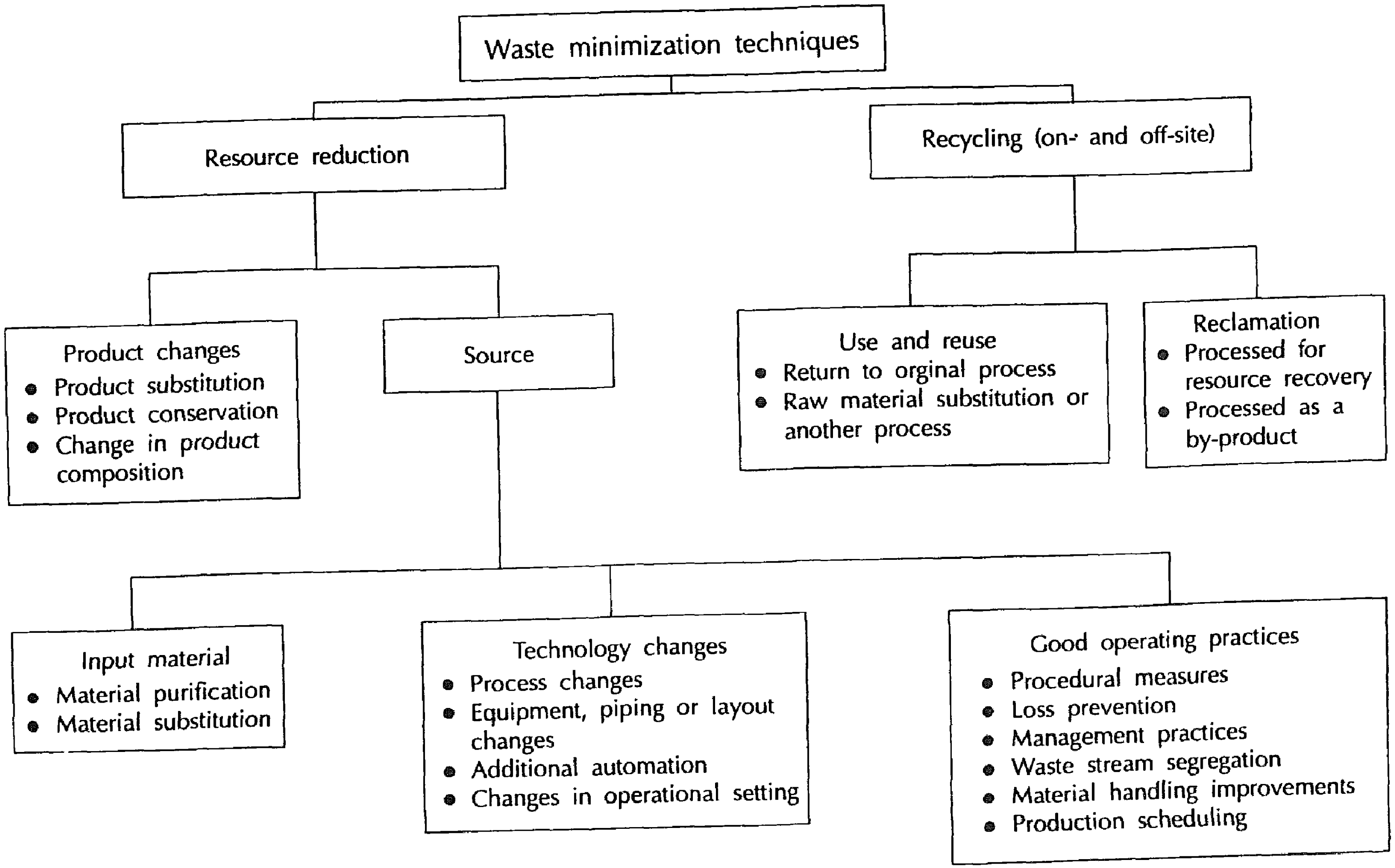

**FIGURE 1.** Waste minimization techniques—a diagrammatic representation.

Implementation of a waste minimization programme is the best defence when a company has to combat with the rising costs of waste disposal and the liability resulting from incorrect disposal such as environmental pollution.

Figure 1 illustrates the techniques that can lead to waste minimization under two broad headings—source reduction and recycling. Each of these aspects is dealt with briefly below.

### *Source reduction*

Under source reduction, the easiest to implement is good operation practices, which largely apply to the human aspect of manufacturing operations. These include:

- management and personnel practices such as training and incentive bonuses to encourage waste reduction;
- loss prevention to minimize leaks and spills;
- material handling and inventory practices to reduce loss of input materials due to mishandling, expired shelf life, and improper storage;
- production scheduling, which can reduce the frequency of cleaning of equipment; and
- waste segregation to reduce the volume of the hazardous wastes by preventing mixing of hazardous and non-hazardous wastes.

The second method of source reduction is to change the technology by:

- process changes;
- equipment, piping, or lay;
- use of automation; and
- changes in operating conditions, namely, (i) flow rates, (ii) temperatures, (iii) pressure, and (iv) residence time.

Process changes are made on a continuous basis in existing plants in order to increase production efficiencies, to make product improvement, and to reduce manufacturing costs; but the primary goal is usually not hazardous waste minimization. The need for this can definitely be expected to increase in the future as hazardous waste management costs increase day by day. Examples of process changes might be as drastic as replacing the mercury cell in the chlor-alkali industry with a diaphragm or membrane cell to avoid the production of a mercury waste and mercury-containing effluent or as simple as replacing a chemical cleaning bath with mechanical cleaning in the metal finishing industry.

The third approach to source reduction is to make input material changes, either by purification or substitution. A starting material of higher purity can lead to a considerable decrease in waste production. The substitution of a higher toxic material by a material of lower toxicity (such as cyanide in the electroplating industry by the considerably less toxic cyanate), leads to a substantial reduction in the toxicity of the wastes produced in the process.

A fourth approach to source reduction is to make product changes with the express intent of reducing the quantity of hazardous waste produced during the manufacturing process and on the disposal of the product at the end of its useful life. A good example of product change is the increasing use of water-based explosives. This not only minimizes the need for the use of organic solvents in the manufacture but also eliminates the problem of disposal of wastes containing hazardous substances like nitroglycerine. The replacement of the highly toxic polychlorinated biphenyl (PCB)-containing oil in transformers with other oils or even using air-cooled transformers is a highly topical example of the problems posed by the need to dispose of a worn-out piece of equipment.

### *Recycling*

The second major waste minimization technique is recycling. Recycling includes:

- use and reuse, which involve the return of a waste material either to the originating process as a substitute for an input material or to another process as an input material; and
- reclamation, in which the waste is processed for resource recovery or as a by-product. Reclamation differs from use and reuse as the recovered material is not used in the facility but is rather sold.

However, recycling options must be carefully evaluated. In the chemical industry, recovery of solvents, oils, lubricants, and metal values has proven particularly cost-effective in many countries. Obviously, the key word here is *cost-effectiveness* since a material of value is not a waste but does, in fact, constitute a resource. However, the increasing cost of the disposal of hazardous wastes, which will occur after implementation of the new minimum standards for landfilling, will make many previously discarded waste materials worth reprocessing. Of course, a financial benefit may not be the only incentive for recycling of a material because a generator may wish to minimize his future liability for incorrect disposal of a hazardous waste under the *polluter pays* principle.

When recycling does not prove to be cost-effective on site, the treatment of wastes from a number of manufacturers may prove to be cost-effective as a centralized facility. Such a facility should preferably be a private sector initiative. Important factors to remember while considering recycling options include the following:

- the legislation and availability of recycling incentives;
- markets for the recycled product and the fluctuations in prices that usually occur;

- quantities of waste to be treated since batches that are too small or too large cannot be economically handled or transported;
- location, since the high cost of transport can easily make recycling uneconomic;
- the existence of harmful impurities;
- capital and operating costs of the recovery process and economies of scale; and
- practicability of the process.

Alternatives for reuse include reusing the material for other purposes, for example, the use of coal ash as an extender in concrete, its transfer to a prospective user through a waste exchange, and the use of certain organic wastes as fuel substitutes.

Once the top management of a company has accepted the need for waste minimization and has given a waste minimization project its full support, the basic approach is to do a waste minimization audit. A waste minimization audit can, however, be accomplished at four levels.

- *Commonsense audit.* The most obvious areas for minimizing the waste produced are attended to. This is easily accomplished in a short time, and can lead to substantial savings.
- *Information-based audit.* Information that can lead to minimization of the waste can be obtained cheaply from waste management companies, consultants, or from the literature.
- *In-depth audit.* A thorough investigation of the processing and manufacturing facility.
- *R & D audit.* Considerable funds and time are spent researching new approaches to waste minimization.

Obviously the first two levels are the easiest and cheapest to accomplish and should be carried out by all companies as a matter of course. Experience gained overseas has shown that the two essential components of any successful waste minimization programme are:

1. the technologies used must be *elegant in their simplicity*; and
2. the production personnel must be strongly motivated to implement and maintain the necessary changes.

Far too often, highly sophisticated technologies or those not properly proven for their application have been applied where much simpler and more well-proven technologies would have sufficed. Also the identification of a project champion, the involvement of the production personnel right from the planning stage of the project, the implementation of a reward and recognition programme and an appreciation of the environmental impacts of waste disposal can assist in reaching the second objective.

Given below are typical information required for a waste minimization audit.

- *Design information.* Process flow diagrams, material and heat balances (both design balances and actual balances) for: (i) production processes; and (ii) pollution control processes, operating manuals and process descriptions, equipment lists, equipment specifications and data sheets, piping and instrument diagrams, plot and evaluation plans, and equipment layout and work flow diagrams.
- *Environmental information.* Hazardous waste manifestos, emission inventories, biennial hazardous waste reports, waste analyses, environmental audit reports, and permits and/or permit applications.
- *Raw material/production information.* Product composition and batch sheets, material application diagrams, material safety data sheets, product and raw material inventory records, operator data logs, operating procedures, and production schedules.
- *Economic information.* Waste treatment and disposal costs, product, utility and raw material costs, operating and maintenance costs, and departmental cost accounting reports.
- *Other information.* Company environmental policy statements; standard procedures, organization charts; chemical characteristics, namely, ignitability, corrosivity, and reactivity; effluent and residue quality standards; siting of treatment and disposal facilities; and cost-effectiveness of treatment and disposal options.

## Treatment and disposal options

### *Choice of technology*

The choice of technology for the treatment and disposal of a particular hazardous and toxic waste will depend on a multitude of factors such as:

- commitment to IWM and waste minimization;
- choice of the best practical means (BPM), best practicable environmental option (BPEO), best available technology not entailing excessive cost (BATNEEC); or the best available technology (BAT) as minimum standard; and
- nature of the hazardous toxic waste concentrating on (i) the physical and chemical characteristics of the waste, (ii) the concentration of the hazardous waste component(s), and (iii) the hazard posed by waste criteria such as mammalian acute toxicity, ecotoxicity, carcinogenic, mutagenic or teratogenic, and environmental fate, both accumulation and persistence.

## *Treatment and disposal technologies*

The number of treatment and disposal technologies available is enormous and the variations on these technologies to be found in the literature are only limited by the ingenuity of scientists, technologists, and engineers, and the nature of the problem. Since the middle of the 1970s, when the environment as an issue received more attention in USA and Europe, considerable technological advances have been made in the treatment and disposal of hazardous and toxic wastes. A brief look at the literature will reveal a plethora of methods and potential applications. Many of these are, however, speculative, unproven, or, at best, emerging technologies, and considerable care must be exercised while selecting an appropriate technology.

Treatment and disposal options that are available fall generally into the following classes:

- physical treatment;
- chemical treatment;
- biological treatment;
- incineration;
- landfill;
- land treatment;
- immobilization, solidification, and encapsulation;
- marine disposal; and
- site rehabilitation and clean-up technologies, and because of its special nature, technologies for infectious (medical) waste.

Any waste treatment technology should destroy the waste or at least, reduce the toxicity of the harmful components in order to minimize its impact on humans, fauna and flora, and the general environment.

Most treatment technologies can be readily adapted and modified to the requirements of a particular waste stream. Many innovative treatment procedures have been developed both locally and overseas. Individual processes or combinations of several processes are used as pre-treatment technologies prior to disposal by landfilling, land treatment, incineration, immobilization, and encapsulation or before disposal at sea. They are also used as primary treatment methods prior to biological treatment, both aerobic and anaerobic or as post-treatment technologies prior to discharge. Also, many processes can be adapted for the recovery of materials during waste minimization and recycling programmes.

### *Physical treatment*

Physical treatment methods are used to remove, separate, and concentrate hazardous and toxic materials. They are considered to be conventional technologies and are commonly used throughout the world. The safety aspects of th processes and the environmental problems that could arise during their use are well known and many processes have been identified as best developed available technology (BDAT). A list of physical treatment technologies is given in Table 1 with a brief description of each process and its typical applications.

### *Chemical treatment*

This would assist in the application of physical treatment technologies, and lower the toxicity of a hazardous waste by changing its chemical nature, often yielding essentially non-hazardous substances such as salts, carbon dioxide, and water. A list of chemical treatment technologies is provided in Table 2 with a brief description of each process and its typical application.

### *Biological treatment*

Biological treatment is a form of disposal in which the final state of the waste is mediated by microbial intervention. Some of the most important points of this treatment for easy reference and completeness have been summarized. There is, of course, a large biological component to landfilling and land treatment (described elsewhere in this volume), and these are discussed only briefly in appropriate sections below. This section deals with those applications in which a carefully selected and controlled form of biological activity is the central process of the hazardous waste treatment. Normally, biological treatment of predominantly aqueous wastes is accomplished in specially designed bioreactors. A suitable culture of the microorganism or microbial association, either aerobic or anaerobic, is chosen. Enrichment, isolation, and genetic manipulation are making it possible to obviate past failures of treatment systems which were inoculated with non-specific microbial associations.

Biological treatment is firmly established as the standard method of waste treatment for some wastes like domestic sewage and certain wastes from food processing. The potential range of hazardous wastes, where biological treatment is appropriate, is extremely diverse and many compounds considered in the past to be recalcitrant have now proven amenable to anaerobic degradation. However, many of the treatments proposed in the literature are unproven although biological treatment technologies, particularly with selected or engineered bacteria, must be considered as the emerging technologies for the treatment of hazardous and toxic waste. The general types of transformations that can be accomplished biologically include:

- degradation of organic compounds to produce carbon dioxide, methane, water, and inorganic salts such as phenols;
- reduction of inorganic compounds such as nitrate; and
- complication of heavy metals such as nickel.

TABLE 1. Physical treatment technologies—description and their applications

| Process | Description | Applications |
|---|---|---|
| Air stripping | Air is passed countercurrent to a normally aqueous waste stream, and volatile wastes are removed from the solution. Cooling or scrubbing the air removes the wastes from the gas. | Removal of low concentrations of ammonia or volatile fatty acids (e.g., acetic acid from water). |
| Electrodialysis | A membrane that selectively retains or permits the passage of specific ions is used. Separation of ions is induced by the application of an electric current. | Recovery of developer in the photographic industry and hydrogen or ammonium fluoride from glass etching solutions. |
| Evaporation | A liquid is vapourized, for example, by heating in order to separate it from dissolved or suspended solids. Unlike distillation, no attempt is made to separate the components of the vapour. | Solar evaporation ponds abound in South Africa for volume reduction of the large amounts of inorganic solutions from chemical and mining industries. |
| Filtration | Solids are removed from a solution by passing it through a filter medium. | Solids are often removed prior to discharge to receiving waters. |
| Flocculation | Small suspended particles are increased in size by the addition of chemicals such as alum, lime, ferrous sulphate, ferric chloride or organic polyelectrolytes. The particles can then be removed more readily by sedimentation or filtration. | Used with hydroxide precipitates in the metal finishing industry, in phosphate removal processes, and for wastes from spray paint booths. |
| Flotation | Air is passed through water containing suspended solids, the bubbles stick to the surface of the required particles and they float on the surface where they are skimmed off. In dissolved air flotation (DAF), the water is pressurized and on the removal of pressure, bubbles are formed. | Flotation is widely used in the mining industry but only DAF has so far found wide application in water treatment such as in the recovery of oily wastes and paint wastes from water. |

| | | |
|---|---|---|
| Ion exchange | An organic resin that has cationic (positive) or anionic (negative) groups can exchange ions with those dissolved in waste water. | Deionization of water to produce high grade water is the most common application, but the recovery of valuable materials such as silver or toxic materials such as Hg and Cr (VI) finds wide use. |
| Reverse osmosis | A semi-permeable membrane that allows only the passage of certain components of a solution is used. Pressure applied to one side of the membrane concentrates the dissolved components on that side. | In the preparation of pure water; the removal of heavy metals such as nickel (II) or Cr (VI) or organic components such as sugars has found wide use. |
| Solvent extraction | A waste solution is contacted with a solvent, such as kerosene or chloroform, having a high affinity for certain dissolved components. Stripping of the solvent results in a product with a high concentration of the desired wastes. | Extraction of phenols from water and deoiling of water in the petroleum industry. Recovery of valuable metals from water or sludges is likely to gain wide acceptance in the future. |
| Waste blending | A waste (solution, sludge or solid) is mixed with an inert solid waste material such as flyash or bottom ash prior to co-disposal to a landfill. | A common procedure is to blend flammable wastes in order to raise the flash point above 61 °C. Ash with a reasonable free lime content is often used to neutralize acidic wastes. |
| Ultra filtration | Ultra-filtration is similar to reverse osmosis except that the semi-permeable membranes have larger pores so that only required molecules of high molecular mass are retained. Lower pressures are also used. | A versatile technology, which can be used for recovery of materials, as diverse as paint, protein from cheese whey, and oil from metal machining wastes |

**TABLE 2.** Chemical treatment technologies—description and their applications

| Process | Description | Applications |
|---|---|---|
| Dechlorination | Reaction of organochlorine compounds with alkali metals such as sodium, alkali metal hydroxides, or with hydrogen and a catalyst. This removes the chlorine and makes the compounds environmentally less hazardous. | Detoxification of PCBs and dioxins. |
| Electrodialysis | An electric current is passed through a solution and the positive ions (cations) go to the cathode where they are reduced and the negative ions (anions) go to the anode where they are oxidized. | Selective removal of metal ions from waste solutions (e.g., silver, copper, cadmium, and nickel). The electrochemical oxidation of cyanide is a BDAT technology for concentrations greater than 300 mg/l. |
| Hydrolysis | Hydrolysis is a process where the elements of water are added to an organic compound. The process is usually carried out in strong acid or base at elevated temperatures. | Hydrolysis of organic waste waters increases their biodegradability. Acid oil sludge from the recovery of used lubricating oils has been successfully treated by this technique. |
| Neutralization | The pH of an acidic or alkaline waste stream is brought to near neutrality by the addition of base or acid respectively. | Neutralization of metal containing acid wastes with lime leads to precipitation of metal hydroxides. Reaction of acid oil sludge with flyash. |
| Oxidation | Oxidation occurs when one or more electrons are added to a molecule. Common oxidizing agents include chlorine, oxygen, ozone, and hydrogen peroxide. | Oxidation of cyanide with chlorine to the less toxic cyanate. Ozone and hydrogen peroxide, with or without u/v treatment, are finding wide application in the removal of toxic organics such as phenols from water. |

| | | |
|---|---|---|
| Precipitation | Some or all come out of the solution as a solid. Common precipitating agents include alkalis, for example, lime, and alkali metal sulphides. | Removal of heavy metals from solution as their insoluble hydroxides or sulphides. |
| Reduction | Reduction occurs when one or more electrons are removed from a molecule. Common reducing agents include ferrous sulphate and sodium sulphite. | Reduction of Cr (VI) to Cr (III) with ferrous sulphate followed by precipitation of chromium (III) hydroxide. |

One of the most important applications of biological treatment technologies widely utilized overseas is the treatment of leachates from landfills. Such treatment can include biological treatment by recirculating through the landfill, by disposal to sewer, or by an on-site bioreactor. These methods are often preceded or followed by physical or chemical treatment.

For convenience, biological waste treatment and exploitation may be divided into aerobic and anaerobic processes, although the two are often used in series and in conjunction with physical and chemical treatment.

*Aerobic treatment.* In aerobic processes, organic matter is removed from the solution by microorganisms through biological oxidation, in which oxygen is consumed by the organisms for energy and new cell mass is synthesized:

Organics + oxygen + N + P → new cells + carbon dioxide + water + non-biodegradable residue.

The organics also undergo progressive auto-oxidation of their cellular mass:

Cells + oxygen → carbon dioxide + water + N + P + non-biodegradable cellular residue.

Often industrial waste waters are discharged to sewers and thus get treated at the municipal sewage works at an activated sludge plant. However, it must be recognized that municipal waste water is very different from industrial waste waters since the BOD consists of predominantly suspended and colloidal matter with only about 40% of it being soluble, whereas in the latter the BOD is almost 100% soluble. The biodegradability of industrial organics is often much lower and they can also be toxic to the biomass, e.g., phenolic compounds. There will also be an effect on effluent and sludge quality. Although discharge of industrial effluent to sewer will continue to be a potentially viable option, the tendency is for the erection of dedicated plants.

It should be noted that the effective biological treatment of hazardous wastes and effluents need not involve the use of expensive plant since typical treatment systems include aerated lagoons, trickling filters, and even oxidation ditches. Other common treatment systems include the rotating biological contactor, fluidized bed reactors, and activated sludge reactors.

*Anaerobic treatment.* Anaerobic decomposition involves the breakdown of organic wastes to gases, namely, methane and carbon dioxide, in the absence of oxygen. The process kinetics and material balances are similar to aerobic processes though there are certain basic differences. The conversion of organic acids to methane gas yields little energy; hence the rate of growth and the yield of organisms are low and thus the rate of organic removal and the sludge yield are also considerably less. High process efficiency requires elevated temperature, although the methane gas produced can be used to provide this heat. One advantage of anaerobic treatment is the methane, which can be used as a valuable energy source or even as a chemical feedstock as for example in the production of cyanide. Anaerobic technology has found ready application in the treatment of food and brewery wastes and it has been shown that anaerobic methods can breakdown a variety of aromatic organic compounds.

### *Incineration*

Incineration is the most common form of thermal treatment of hazardous and toxic wastes. Thermal treatment can include technologies such as sterilization and pyrolysis, which involves the thermal degradation of organic material, usually in the complete absence of oxygen, and wet air oxidation, which is a form of chemical oxidation.

Incineration is the controlled combustion of waste materials to a non-combustible residue or ash and exhaust gases, which are carbon dioxide and water. The combustion of wastes containing sulphur and chlorine can lead to considerable quantities of acid gases such as sulphur dioxide and hydrochloric acid; but these can be scrubbed from the gas stream prior to discharge to the atmosphere. In USA and Europe, incineration is preferred and even specified for BDAT for many organic hazardous and toxic waste streams. There are different types of incineration technologies used for the treatment of hazardous and toxic waste. These include:

- rotary kiln furnace;
- multiple hearth furnace;
- fluidized bed furnace;
- liquid injection furnace;
- multiple chamber furnace;
- gas furnace;
- catalytic furnace;
- electric furnace;
- molten salt furnace;
- high temperature fluid wall furnace; and
- emerging technologies such as the plasma arc furnace.

The choice of the furnace is largely determined by the nature and form of the waste to be incinerated. However, rotary kiln, multiple hearth, and fluidized bed furnaces have been shown to be the most versatile for mixed or general hazardous waste streams. One important innovation is the burning of hazardous and other wastes as fuels in cement kilns.

Hazardous waste normally requires very high temperature (up to 1250 °C) and long residence time (one to two seconds) for complete combustion of thermally stable materials such as PCBs. Rapid quenching of the flue gases is often required in order to prevent recombination of the gases into the highly thermodynamically stable dioxins.

The major advantages of incineration in a modern well-run facility is that the waste, apart from the residual ash which must be landfilled, is destroyed, and the future financial liability of the generator under the *polluter pays* principle is minimized. The need for (1) considerable atmospheric pollution control equipment, which often costs more than the combustor itself, (2) the sophistication of the equipment, required for the safe handling and analysis of highly toxic materials, and (3) highly trained staff contributes to the high cost of incineration. An incorrectly operated facility will often pose a greater threat to the environment than the original waste. However, incineration is normally the technology of choice if the waste:

- is biologically hazardous;
- is resistant to biodegradation and is persistent in the environment;
- is volatile and therefore easily dispersed;
- has a flash point below 40 °C;
- cannot be safely disposed of in a landfill site; and/or
- contains organically bound halogens, lead, mercury, cadmium, zinc, nitrogen, phosphorus or sulphur.

There are a number of advantages in the use of selected hazardous wastes as fuels in cement kilns. They are: (1) the high temperatures (up to 1500 °C) that are reached in order to manufacture the cement clinker; (2) the long gas residence times (up to six seconds); (3) the automatic scrubbing of noxious gases such as hydrogen chloride from the gas stream by the alkaline conditions in the kiln; and (4) the savings in conventional fuel such as coal. Since they are existing facilities, there is usually less public opposition to their siting, and capex required is only about 10% of that needed to build a dedicated chemical incinerator. Currently, there are over 25 cement facilities in USA burning more than one million tonne of hazardous waste fuels per year. The disadvantage is that only limited amounts of certain hazardous constituents can be added (e.g., heavy metals, sulphur, and chlorine) due to their effect on the operation of the kiln or the quality of the clinker. Further, the increase in costs of monitoring the stack gases and the fact that the waste should preferably have a reasonable calorific value make pretreatment often necessary. However, it is clear that the emissions from cement kilns burning hazardous waste fuels pose no hazard to human health or the environment. Other wastes that are burned include tyres and refuse derived fuels.

### *Landfill*

The disposal of hazardous and toxic wastes, after appropriate treatment, to landfills is the most common method of disposal and is likely to remain so in the foreseeable future. In general, the standards for landfills are expected to increase in the future as knowledge of landfilling technology improves, because of the risk of pollution posed by the practice of landfilling. The current trend overseas is to minimize the disposal of many organic wastes to landfills, although our knowledge of technologies such as co-disposal is increasing through a number of research programmes both in Britain and in South Africa.

### *Land treatment*

Land treatment of wastes is a form of disposal in which the final state of the waste is mediated by intimate contact with the soil. Conventional farming technology is creatively adapted to dilute and to chemically or biologically inactivate solid and liquid wastes over relatively large areas of land. Lined cells containing appropriate soil is however utilized under special conditions. The principle is that land treatment exploits the natural capacity of the soil to return substances to a condition approaching the original state from which they were won by a process of extraction and purification. In theory, almost all wastes can be treated by land treatment though our knowledge of the mechanisms of attenuation, dispersal, and biological degradation is extremely limited.

In planning a land treatment facility, a large number of factors need to be considered including the climate, topography, geology, soil types, and the infiltration and run-off potential of the soil. Provision for diversion of the run-off that would be generated both in normal and abnormal weather conditions must be made. Trials need to be conducted to ensure that the waste can be successfully treated and a very strict monitoring programme must be instituted and maintained throughout the life of the site in order to ensure that the treatment remains successful and pollution does not occur. The technique has proved very useful for the rehabilitation of land contaminated, particularly by petroleum wastes. Land treatment is often a very cheap method for the disposal of wastes but in general it is not favoured because of the high pollution potential of the technology.

### *Immobilization, solidification, and encapsulation*

The main objective of immobilization, solidification, and encapsulation techniques is to convert the hazardous and toxic waste into an inert, physically stable mass, with a very low leachability and sufficient strength to allow for landfilling or land reclamation. Definitions of these processes are given below.

- Immobilization (or chemical stabilization) is a process in which the waste is converted to a more chemically stable or more insoluble or immobile form.

- Solidification or cementation is a process in which the waste is converted to an insoluble rock-like material by mixing with suitable materials to form a solid product.
- Encapsulation is the coating or enclosure of waste with an inert durable material. Micro-encapsulation is applied to the individual particles of a waste, while macro-encapsulation is the encapsulation of a mass of waste in a container.

The most common materials used are cementing agents such as portland cements, lime, flyash, and gypsum mixtures. However, although highly successful in reducing the mobility of wastes, cementation methods often lead to a considerable increase in volume, for example, the solidification of 40 litres of radioactive waste can increase the volume to as much as 100 litres, thus considerably increasing the cost of both transport and disposal. However, new products based on heat-treated natural clays have recently become available. These are capable of absorbing liquid wastes and sludges, either organic or inorganic, to produce products that easily pass normal leachability tests. The increase in volume observed with these products is only of the order of 20%. Also used are bitumen, polymers such as polyethylene, styrene-divinylbenze co-polymers, and glass materials, which are used in a process called verification (but this has largely been applied to radioactive wastes).

It is clear that these types of processes, which would greatly reduce the mobility of wastes in a landfill, should be playing a much more important role in the disposal of wastes to landfill. Wastes with relatively high concentrations of hazardous materials could be immobilized and, therefore, disposed as a waste with a much lower pollution potential. The leachability test devised by the US EPA is called the toxicity characteristic leaching procedure (TCLP) in which acetic acid or acetate buffer is used to leach the treated material. Solidified products which pass the test, i.e., which give a leachate concentration below a specified lower limit, are considered non-hazardous. Typical wastes that could be successfully treated by this procedure would be those containing arsenic, mercury, and even quantities of high hazard pesticides. The use of solidification processes can greatly reduce the *effective* concentration of waste disposed to a site and thus could be used to limit the amount of macro-encapsulation in specially designed cells of a variety of both inorganic (such as arsenic) and organic wastes (such as pesticides), and/or PCBs that are contained in sealed (usually 210-litre) drums. The cell is constructed within an appropriate containment landfill and is designed to minimize the potential leakage of wastes from the cell and is of such a size that damage due to earth movement and earthquakes is likely to be minimal. Macro-encapsulation of inorganics will always have an important role to play but it is preferable to incinerate organics rather than encapsulate them if the technology is available. It must be emphasized that macro-encapsulation is a storage technology and we are simply leaving a legacy for our children.

### *Marine disposal*

Marine disposal can be carried out in a number of ways. The main ones are: (1) discharge using a submarine pipeline; (2) incineration at sea; (3) dumping from vessels and barges; and (4) encapsulation and burial in deep-sea sediments. The technology relies on the powerful dispersing capability of the sea, its ability to biodegrade many organic wastes, and the sequestering ability of sea sediments. Marine disposal can prove to be a very cheap option and has been widely used, particularly for sewage in the coastal areas. A properly designed outfall has two major objectives:

1. to achieve a high initial dilution of the discharge effluent; and
2. to remove, or operate the effluent from the shore or any other sensitive area, far and deep enough.

Examples of wastes that are currently being disposed by this technology include neutralized phosphogypsum from the fertilizer industry and lignin wastes from paper and pulp industry.

The *International Convention on the prevention of marine pollution by dumping of wastes and other matter (1975)*, commonly known as the London Convention, has listed (*black list* or Annex 1) highly hazardous substances that are prohibited from dumping. The list includes familiar materials such as organohalogens, mercury, and cadmium and their compounds, persistent plastics, radioactive wastes, and crude oil and its wastes. Annex 2 or the *grey list* gives compounds that can be dumped on issue of a special permit. Due to past misuse and many misconceptions, marine disposal has met with wide public disapproval throughout the world and its use is declining rapidly.

### *Site rehabilitation and clean-up technologies*

The choice of strategy and a process for the clean-up and rehabilitation of a site should be done on the basis of a detailed risk assessment that includes a hazard evaluation, exposure assessment, and risk characterization. However, the initial response should be to clean up the most obvious sources of pollution such as old drums and stockpiles as well as obviously contaminated soils, and to contain potential run-off water on-site in order to minimize further pollution. Disposal of the removed materials should be to a permitted landfill after appropriate treatment, which could include incineration. Once this has been done, the long and often arduous task of assessment of the extent of the pollution and choice of rehabilitation strategy must take place. The strategy should be developed after an extensive investigation of the site, which could include analysis of soils, both on- and off-site, from trenches and the analysis of surface water, and groundwater from existing and specifically drilled boreholes.

The most common technologies used in USA during 1987 were, in order of importance, engineering containment, incineration or other thermal treatment, solidification/stabilization/neutralization, volatilization or soil aeration, biotreatment, and vacuum extraction. The main aim of engineering containment is to limit the movement of surface or groundwater into the contaminated area or prevent contaminant migration from the site. Options include the provision of covers as for site closure or vertical barriers by slurry trenching or cut-off or diaphragm wall technology. The other treatment technologies are simply variations of those described in the previous sections. Two of these—bioremediation and volatilization—are discussed below.

*Bioremediation.* Bioremediation technology uses the principles discussed in the section on biological treatment and can be applied to extracted groundwater and treatment of eluates from soil flushing; but its most rapidly growing use is the *in situ* treatment of subsurface materials, which have been contaminated by organic materials. *In situ* bioremediation usually involves stimulating the indigenous microflora to degrade the contaminant in place although special microflora has been seeded in some cases. The aim is to convert the organic contaminants to carbon dioxide, methane, and inorganic salts. The factors affecting the feasibility of *in situ* bioremediation are:

- available oxygen concentration;
- levels of macro-phosphate, nitrogen, and micro-nutrients (zinc, magnesium, etc.);
- redox potential of the soil;
- soil pH;
- soil temperature;
- hydraulic conductivity of the soil;
- competition of contaminants; and
- presence of toxins and predators.

*Volatilization.* Volatilization (or soil venting) methods have proven to be highly effective for the removal of volatile compounds from soil by using commercial units that heat up the soil to between 100 and 500 °C. Even PCBs have been removed in rotary dryers at temperature of 350 to 550 °C. Soil venting or aeration can be either passive as when pipes are put in the ground to allow landfill gas to escape or active as when air is pumped into the soil or a vacuum applied. The resulting gas stream in all these methods has to be treated in order to remove the contaminants. The resulting waste must then be subjected to further treatment if necessary before sending for final disposal.

## INFECTIOUS (MEDICAL) WASTE

Infectious waste is waste from hospitals (generally termed as medical or clinical waste), biological research facilities, and water analysis laboratories. The current increase in genetic engineering research results in potentially infectious materials, whose properties are often entirely unknown. All over the world, the rapid increase in AIDS is a major cause for concern. The high incidence of hepatitis B and other diseases (such as cholera, typhoid, and even tuberculosis, which have largely been eradicated in the First World) increases the risk of cross infection from these wastes in less developed areas. Infectious waste is, thus, classified as Group 1 or extreme hazard waste.

Four different waste streams have been identified as arising from hospitals. They are:

1. infectious hazardous waste;
2. chemical hazardous waste;
3. municipal solid waste including food wastes; and
4. radioactive wastes, both low level such as $^{127}I$, $^{3}H$, $^{14}C$, and high level ones such as $^{57}Co$.

There are a number of technologies, such as incineration, microwaving, autoclaving, disinfection, and grinding at temperatures of 200 °C. Except for incineration, most of the above technologies do not greatly reduce the volume and in all cases, some material is left behind that must be landfilled. In the case of incineration, the waste is, however, reduced to at least 10% of its original volume and syringes and needles are rendered unusable. Incineration is thus the technology of choice in many countries although public concerns about the possibility of air pollution from the incinerators have led to increased costs for appropriate pollution control measures.

There are a number of innovative systems that have been developed for the handling of infectious waste. In one of these, two basic containers are used to dispose of infectious waste products. The most effective one is a moulded polypropylene container with a slot in the top. This container is always available at the operating table or in the ward to drop in contaminated instruments, needles, and syringes. For wastes such as placentas, dressings or swabs, a large cardboard box lined with a red garbage style bag is used. Both containers are marked with the universal bio-hazardous symbol. The wastes are transported in

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# Economic policies and analysis in effluent treatment and financial constraint

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## INTRODUCTION

Fixing the minimal standard for every industrial unit across the board is impracticable. It would be much less expensive if we ask some units to abate more and some others to abate less, depending upon the abatement costs. The total cost will be less than what it would have been if each industry was to reduce pollution equally. Table 1 will illustrate this theory.

As per the command and control mechanism of prescribing equal performance standards, it will cost Rs 43 200 to bring down pollution to a total of eight units. But this is not the best solution to the pollution problem. The same results could have been achieved if X was asked to reduce pollution down to six units and Y down to two units at a total cost of Rs 22 800 only. The country's products could have been more competitive in international markets.

**TABLE 1.** Pollution abatement costs in firms X and Y

| Firm X | | Firm Y | |
|---|---|---|---|
| Pollution (units) | Cost (Rs) | Pollution (units) | Cost (Rs) |
| 10 | — | 10 | — |
| 9 | 1000 | 9 | 100 |
| 8 | 2500 | 8 | 200 |
| 7 | 5000 | 7 | 400 |
| 6 | 10000 | 6 | 800 |
| 5 | 20000 | 5 | 1600 |
| 4 | 40000 | 4 | 3200 |
| 3 | 80000 | 3 | 6400 |
| 2 | — | 2 | 12800 |
| 1 | — | 1 | — |

specially designed and distinctive vehicles to a centralized incineration facility. After weighing, the boxes are incinerated in a dual-chamber incinerator. The boxes are ram-fed into the first chamber where they are burnt at a temperature of around 800 °C in a slight stoichiometric deficit of oxygen. The gas, which contains small amounts of pyrolysis products, is burnt in the second chamber at 900 °C in a stoichiometric excess of air. Diesel is used to supplement the fuel requirements of the incinerator. Experience has shown that the stack emissions readily conform to existing atmospheric pollution regulations including the USA standards set by the EPA. In order to achieve such results, the need for an experienced and skilled operator cannot be emphasized strongly enough.

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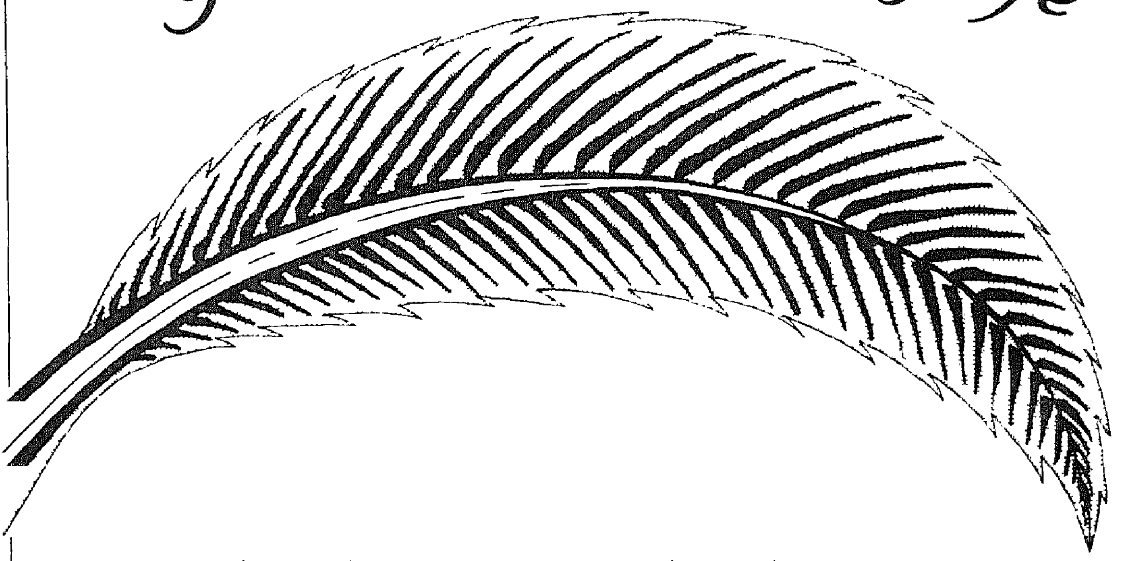

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One method of providing this kind of incentive is to design a pollution charge structure where each unit will have an option, i.e., either to abate pollution or to pay tax. When the cost of abating pollution is less than the tax, each unit will try to reduce pollution and when it becomes more than the tax, they will pay tax and discontinue pollution abatement efforts. Table 2 shows how the two firms (X and Y) will behave when there is a pollution charge structure affecting them differently. To make the scheme more effective in terms of reducing costs and pollution, the charges collected from firms with higher abatement costs can be given to firms with lower abatement costs.

One economic instrument automatically makes the payment from the more expensive abator to the less expensive abator without the interference of the government. The less expensive abator reduces his pollution on payment from the more expensive abator and this is done in a *pollution market.* A pollution market will function more or less like a share market. This instrument is called *pollution credit* or *tradable permits.* The following example will make the concept very clear. There are four polluting factories in a watershed as shown below.

1. Firm A pollutes three units
2. Firm B pollutes seven units
3. Firm C pollutes five units
4. Firm D pollutes 10 units

The given premise is that the existing pollution is acceptable and no further pollution will be allowed (the cap can be at a lower level also, but an initial allocation of permits has to precede the operation of the markets). At this point,

**TABLE 2.** Differing pollution charge structure for firms X and Y

| Abatement costs of firm X (Rs) | Abatement costs of firm Y (Rs) | Pollution charges (Rs) | Quantum of pollution (points) |
|---|---|---|---|
| — | — | 10000 | 10 |
| 1000 | 100 | 9000 | 9 |
| 2500 | 200 | 8000 | 8 |
| 5000 | 400 | 7000 | 7 |
| 10000 | 800 | 6000 | 6 |
| 20000 | 1600 | 5000 | 5 |
| 40000 | 3200 | 4000 | 4 |
| 80000 | 6400 | 3000 | 3 |
| 160000 | 12800 | 2000 | 2 |
| 320000 | 24000 | 1000 | 1 |
| 640000 | 48000 | — | 0 |

firm C wants to expand operations by starting another factory. It chooses a clean technology, yet it would pollute three units. It can start the new factory if it can reduce pollution from its old factory equivalent to three units, which will cost firm C Rs 1000 per unit. So, it approaches D which says it will take Rs 700 per unit though his own pollution reduction would cost only Rs 300. Firm C goes to B whose cost will be Rs 400 but demands Rs 500 from C. It goes back to D and says that it would accept the offer of B unless D is willing to reduce further. Firm D finally agrees to cut down three units of pollution, for a payment of Rs 400 per unit.

However, there is no need to engage in mutual negotiations like this. Once tradable permit scheme becomes operational on a nationwide scale, an industrialist will be able to go to a broker and buy permits at the prevailing market rates. Markets will develop as in the case of shares and according to demand and supply, the price of the permit will fluctuate. In these markets, the right to use environment as a waste sink is priced and traded. Pricing would reduce the use of the environment as a waste sink because the more it is used the more it costs. Trading would ensure that the assimilative capacity of the environment as a scarce resource is put to the best use, and used sparingly, that is, the minimum amount of waste per unit of economic output (gross domestic product) is discharged into the environment. As industrial activity increases, the price of permits is bound to increase and this will encourage technological innovation in cleaner production technologies.

A concept of global permit trading in greenhouse gases (GHGs) and forests is also being considered vigorously. The countries which have rich forest reserves can sell off the permit to emit GHGs to firms in the west, who then can engage in activities which emit GHGs.

There are some problems with this system. In the above example, the government had decided that no more pollution would be allowed. But this is fixing a premium on earlier pollution. A unit with a record of high pollution, and which made no efforts to reduce pollution till the advent of this scheme, would now find it easy to reduce pollution; they can earn money from the new units at comparatively lesser costs than a unit which has been sincerely trying to reduce pollution even before the scheme had started. The second unit has already reduced pollution to a level from where the subsequent pollution reduction is very costly.

There is one method in which the government can allot fresh pollution permits, by taking into account the efforts the units have already put in. In that case, even at the time of initial allocations some units will have surplus permits and some others will have a deficit. Therefore, each unit will try to present its facts in such a way as to enable it to get more permits. The permit allocating officer or politician will have a lot of discretion as he will be doling out huge sums of money to some units and put a financial burden on others. One way to circumvent this difficulty is to auction permits. However, there is difficulty in implementing this when local communities refuse to allow units to buy permits and pollute their immediate environment.

If it is an air shed or a watershed that is being polluted, there is no reason why local people should object. However, some of the tradable permit systems are designed for the whole country. For example, the sulphur dioxide emission permit scheme in USA is for the whole country, and a unit in the south of the country may buy permits from a firm in the north. As it will take some time for the dispersal of the pollutant in the air, the local people may not be willing to tolerate that. However, in certain kinds of permit markets, this problem may not arise. For example, permits for the use of virgin pulp by paper mills or inter-refinery trading of lead credits would not face this problem.

In India, or in other developing countries, the small-scale units cannot be brought into pollution markets. But such markets can be developed for bigger units discharging the same pollutants. Pollution trading does not apply to more than one pollutant simultaneously, unless some equivalence index is developed.

There is another difficulty. The government will have to decide whether in a particular watershed or air shed, the existing pollution is of the right level or whether there is a need to reduce it. On what ground would the government take such a decision? It could be on the basis of the pollution level that is desirable for the area. What the desirable pollution level for an area or a country would be is a tricky question. Experts may express different opinions because the parameters involved and their interrelationships are not objectively precise. Considering all the scientific opinions, the ultimate decision has to be taken by the local community.

Environmental economics has developed certain tools for assessing public opinion. What the economists should do is to calculate the cost of the operation for reducing pollution to a certain level and to find out whether the society is really willing to spend that much on controlling pollution and, if not, how much it is willing to spend.